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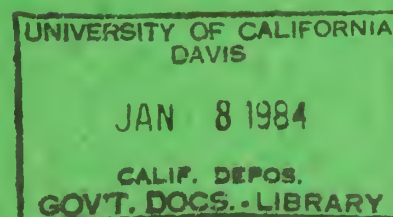
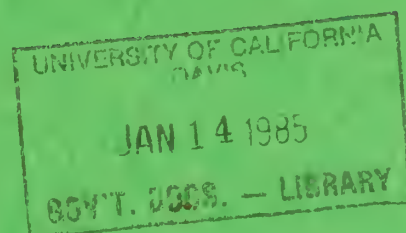
## Effects of Various Chemicals on the Laboratory Shear Strength of an Expansive Soil

1984

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CALIFORNIA DEPARTMENT OF CONSERVATION  
DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 155





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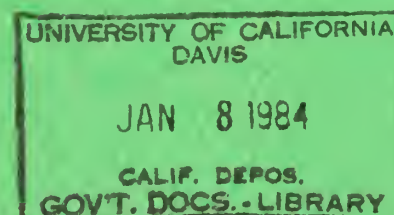
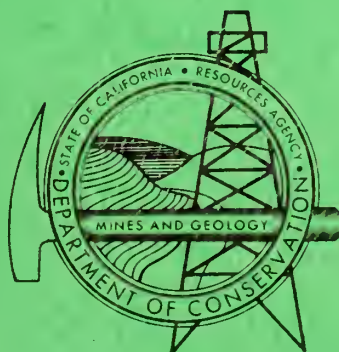
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DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 155







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# **SPECIAL REPORT 155**

## **STABILIZATION OF LANDSLIDES**

### **Effects of Various Chemicals on the Laboratory Shear Strength of an Expansive Soil\***

by

Glenn Borchardt

Soil Mineralogist

1984

California Department of Conservation  
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\*Originally released as Open-File Report 78-9 SF.



## PREFACE

The purpose of this report is to evaluate the effectiveness of various chemicals as additives to expansive soils (such as the smectitic Diablo clay) for stabilizing slopes against landsliding. Effects of various chemicals upon the shear strength of Diablo clay are examined to find the chemicals that produce precipitates, or cementing agents, in the soil.

The report will be of interest to scientists and government officials who are concerned with the problem of stabilizing failure-prone slopes, as well as residents of hilly or mountainous areas throughout the state.



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## GLOSSARY

*C HORIZON:* That part of a soil profile occurring beneath the A horizon (leached oreo) and the B horizon (oreo of clay accumulation) that is least weathered and probably represents material similar to that from which the soil formed.

*HIGH-MOISTURE STRENGTH:* Defined in this study as the shear strength at a water content near the liquid limit (86% for Diablo clay.)

*LEACHING:* The process whereby materials are dissolved or suspended in water and removed from the soil.

*LIQUID LIMIT:* The percent moisture at which a soil changes from plastic flow to liquid flow.

*LOW-MOISTURE STRENGTH:* Defined in this paper as the shear strength at a water content near the plastic limit (21% for Diablo clay).

*NEUTRALIZATION:* The addition of either acid or base to obtain neutrality in which the activity of the  $H^+$  ion is equal to the activity of the  $OH^-$  ion producing a pH of 7 at standard temperature and pressure. Buffer systems, such as soils, have a slight tendency to return to the original pH after rapid neutralization.

*PLASTICITY INDEX:* The liquid limit minus the plastic limit; related to the degree of soil expansibility.

*PLASTIC LIMIT:* The percent moisture at which soil begins plastic flow.

*REMOULDING:* The process in which a soil sample is reworked or kneaded prior to determination of the shear strength.

*SHEAR STRENGTH:* The resistance to movement by shear displayed by a material, expressed as mass per unit area.

*SYMMETRY:* The percentage of an adsorbed cation displaced by an amount of salt equivalent to the cation exchange capacity.

*WATER CONTENT:* The amount of water in a soil sample expressed as a percentage of the oven dry weight (heated for 24 hours at  $110^\circ C$ ).

*WEATHERING:* A group of natural processes whereby a rock or soil is physically and chemically altered. The processes include chemical action of air and water; the physical and chemical influences of plants, bacteria, and animals; and the physical processes of ice wedging, frost heaving, and abrasion. It was artificially simulated in this study by neutralization and leaching.



## ABSTRACT

The value of a structure built on an unstable soil may warrant stabilization by chemical means. The literature reveals extensive work on soil stabilization with chemicals but only scattered references to applications of chemicals to soils in landslides. The objective of this study is to evaluate chemicals that theoretically should affect the shear strength of expanding layer silicates such as the most common smectites, montmorillonite and beidellite.

A systematic procedure was developed in this study to test the ability of various chemicals to increase the shear strength of Diablo clay. This is a highly expansive, smectitic soil that is prone to landslides. Five-gram portions of the chemicals were added to 60 ml of water, which was mixed with 100 g soil samples in 200 ml beakers. The effects of these treatments were monitored by determining liquid and plastic limits. Shear strengths also were measured at varying moisture contents by using the torsion vane. Samples were then neutralized with hydrochloric acid or ammonium hydroxide and leached of excess salts in order to simulate a likely result of soil weathering. Data are presented in the form of curves of water content plotted against the log of the shear strength of the soil.

In general, high concentrations of salts in the pore solution of Diablo clay decrease the liquid limit and the shear strength at high moisture levels. Weathering, as simulated by neutralizing and/or leaching, causes chemically treated soil to regain or exceed the original strength at high moisture levels.

Most *chloride* salts decrease shear strength at high moisture levels. Improvements in high moisture strength were noted only after subsequent neutralizing and leaching of the soil. The acidic chlorides of ferric iron and aluminum react with the hydroxide ion to form polymers that enter the interlayer spaces in smectites. This reaction increases the liquid limit and the high-moisture shear strength above values produced by leaching alone.

The *fluoride* salts increased shear strength at all moisture contents. HF produces up to a three-fold gain in strength within one day. HF in excess of 5 g/100 g soil produces no deleterious effects, whereas neutral KF does. The cementing agent produced by HF is a fluosilicate that is relatively insoluble and extremely resistant to leaching. Potassium fluoroaluminate and fluoroferate produced by KF are slightly soluble and, thus, shear strength will decrease gradually as the cementing agent is leached away.

The *hydroxides* of Ba, Ca, and K increase the shear strength of smectitic clay while decreasing its expansibility. About 1% calcium hydroxide reacts with Si and Al to form cementitious compounds that permanently increase the shear strength at moisture contents below 50%. Such lime-treated landslides must be well drained so that the moisture content never exceeds 50%. NaOH increased the liquid limit and the strength at high moisture contents while increasing the expansivity—a property normally considered deleterious.

*Organic chemicals* such as Armoc T and ethylamine-HCl decreased soil expansivity and shear strength at high moisture levels. Strength improvements occurred only at low moisture levels. Physical mixing appeared necessary to achieve contact with the soil. Many compounds that are soluble enough to penetrate landslides also are soluble enough to be leached away by rainfall.

The acidic *phosphates* form insoluble iron and aluminum precipitates that act as cementing agents in soils. Phosphates increased shear strength at moisture contents below 60%. Subsequent neutralizing and leaching further enhanced this strength development, and the treatment appears permanent.

Ferrous *sulfate* doubled the liquid limit and increased the shear strength at high moisture contents after the neutralizing and leaching step. Other sulfates, such as ammonium sulfate, produce only marginal and temporary increases in shear strength. Ferric sulfate treatment of a non-expansive clay mineral, kaolinite, resulted in little change in shear strength. Thus, ferrous sulfate produces dramatic increases in liquid limit only in soils in which ferrous hydroxide precipitates between the layers of an expansive clay. The smectite in our test soil, Diablo clay, is such an expansive clay.

In conclusion, various chemicals tested in this study produce effects dependent upon moisture content and degree of "weathering" (neutralizing and leaching). Calcium hydroxide, phosphoric acid, KF, and HF produce immediate and lasting increases in shear strength in smectitic Diablo clay. This is most likely because of the precipitation of insoluble cementing agents that bind soil particles together. The interlayering of expansive clay with hydroxy polymers involves a two-step process. This process often decreases shear strength before increasing it. For the most part, cation exchange with neutral salts appears to be insignificant when only 5% quantities of salt are used to treat the soil.





# STABILIZATION OF LANDSLIDES

## Effects of Various Chemicals on the Laboratory Shear Strength of an Expansive Soil \*

By

Glenn Borchardt, Soil Mineralogist

### INTRODUCTION

California suffers an average of \$300 million per year in damage as a result of landslides (Alfors, Burnett, and Gay, 1973). The benefit/cost ratio for efforts to reduce damages caused by landslides is estimated to be approximately 20 times the benefit/cost ratio commonly used to justify flood control projects. The simplest way to reduce damages resulting from landslides is to avoid building on unstable slopes. When a landslide becomes active after construction, expensive procedures are necessary for abatement. Drainage is usually attempted at first, followed by removal of the sliding material. Occasionally, the value of a structure built on unstable soil may warrant stabilization by chemical means. Unfortunately, most of the work with chemical stabilization of soils has involved the preparation of roadbeds in expansive soils rather than landslides (Ingles and Metcalf, 1972).

The differences between the problems of expansive soils and landslide soils provide a point of departure for testing chemical treatments. Shear strength rather than expansion is the soil property of concern when dealing with landslides. The experiments described herein rely upon some of the basic knowledge discovered since the fine review by Mielenz and King (1955). An understanding of soil chemistry, clay mineralogy, and their relations to the problem of landslide stabilization may lead to the discovery of new information on the factors responsible for landslides as well as the measures necessary to stop them.

### ACKNOWLEDGMENTS

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### CONCLUSIONS

The chemical stabilization of landslides containing expansive clays can best be carried out with chemicals that produce precipitates or cementing agents in the soil. Of all the chemicals tested, hydrofluoric acid produced relatively rapid and permanent increases in shear strength at all moisture contents. Concentrations between 4 and 10 g HF/100 g of Diablo clay increased the shear strength by a factor of three. Ion exchange did not appear to be a significant contributor to shear strength when only 5% amounts of chemicals were added. Neutralized  $Al^{3+}$  and  $Fe^{2+}$  appeared to form chloritic interlayers that increased liquid limits and strength at high moisture contents. Chemicals

other than HF also produced changes in physical properties of the test soil. The most important conclusions for the seven chemical groups are given below.

### Chlorides

In general, the chloride salts have one major disadvantage for stabilizing smectite-bearing landslides—they first lower the shear strength before increasing it. For non-expansive clays, the results could be the opposite. Increasing the ionic strength of porewater associated with expansive clay causes the liquid limit and high-moisture strength to decrease. In these experiments, each of the neutral chlorides decreased the liquid limit (LL) from 86 to 61. The acidic chlorides were of similar weight but higher ionic strength and probably were involved in complex reactions forming polymers that block the collapse of smectites.

Both the liquid limit and shear strength increase when excess chlorides are leached from the soil by rainfall or artificial means and the effects of cation exchange begin to appear. How much cation exchange occurs and how much the physical properties of the clay are altered from the natural condition depends upon several important factors: (1) the type of cations on the exchange of the clay, (2) the type of cation being added, (3) the type of minerals responsible for the cation exchange capacity (CEC), (4) the CEC of the soil, and (5) the ionic strength of the porewater during cation exchange. Increases in shear strength produced by cation exchange are likely to correspond to increases in the liquid limit.

The "replacing power" of small, highly-charged cations such as  $Al^{3+}$  is much greater than of large, monovalent cations such as  $K^+$ . This is best illustrated by the sample treated with aluminum chloride. After leaching the excess salts away, the LL (liquid limit) of this sample was reduced from 86 to 70. This was the greatest permanent change in LL, and presumably indicates that, of the eight chlorides studied, Al produced the greatest amount of cation exchange.

In general, increases in the concentration of most soluble salts, such as NaCl,  $MgCl_2$ , and KCl, etc., in pore solutions of Diablo clay usually result in decreases in shear strength at high-moisture levels and an increase in strength at low-moisture levels. High salt concentrations decrease the liquid limit, but plastic limits (PL) may increase slightly. Leaching generally increases the LL of Diablo clay treated with the above salts. The slope of the shear curve tends to return to that of the untreated soil.

Aluminum chloride increases shear strength at moisture contents below 40%, but decreases strength above this. Leaching of  $AlCl_3$  caused a slight increase in strength. Partial neutralization and leaching of  $AlCl_3$ -treated soil with ammonium hydroxide,  $NH_4OH$ , increased the shear strength at moisture contents above 30%. There was a corresponding increase in the LL to 108.

Ferric chloride,  $FeCl_3$ , had no effect on Diablo clay except for a small decrease in plasticity index. A small increase in LL and shear strength occurred after neutralization and leaching of the soil.

\*Originally released as Open-File Report 78-9 SF.

Potassium chloride, KCl, decreased shear strengths at high moisture until it was leached, producing a net increase in strength at moisture contents above 20%. The LL increased from 62 to 97 as a result of the leaching step.

### Fluorides

The soluble fluorides, HF and KF, produce rapid and substantial increases in shear strength at all moisture levels. HF reacts with Si to form fluosilicates that seem to precipitate between the layers in smectites. The great insolubility of these fluosilicates prevents them from being leached away by rainfall. The reaction is complete in less than a week. Excess amounts of HF (greater than 5% for Diablo clay) are neither detrimental nor helpful to the newly developed shear strength. Disadvantages of using HF for landslide stabilization include its high cost and acute handling problems.

KF produces strength-gains by reacting with Al and Fe to form potassium fluoraluminate and fluorferrate. These compounds also appear to precipitate between the layers in smectites. The reaction is almost complete within 30 minutes after application. Unfortunately, fluoraluminate is slightly soluble (1.4 g/l) and would be leached slowly from the soil by rainfall. Unlike HF, however, excess amounts (greater than 5%) of KF are counterproductive because the unreacted KF increases the ionic strength of soil porewater, causing smectites to collapse and shear strength to decrease.

### Hydroxides

The hydroxides of Ba, Ca, and K increase the shear strength of Diablo clay while decreasing its expansibility. Calcium hydroxide adsorption produces a rapid and dramatic rise in the plastic limit of smectitic clay. This adsorbed lime rapidly increases the shear strength at moisture contents below 50% for Diablo clay. About 1% of the lime (an amount about equivalent to the calcium saturation of the soil) then reacts with Si and Al to form cementitious compounds. These maintain the shear strength even after the adsorbed calcium hydroxide disappears. The disappearance of calcium hydroxide is attributed to neutralization by soil acids or leaching by rainfall. It also reacts with carbon dioxide to form relatively inert calcium carbonate. Carbonation of lime is most rapid whenever the soil is dried in the air. The cementitious compounds are highly insoluble, and they appear unattacked by HCl or leaching. Most of the changes in shear strength produced by lime are permanent. However, good drainage must be provided to avoid the low strength produced by excess pore pressure at high moisture levels.

The hydroxides of Ba and K produce some effects similar to those produced by lime. NaOH, on the other hand, increases shear strength and expansivity, both of which continue to develop as the excess NaOH is leached away. In 5% proportions NaOH appears highly effective in producing a Na-saturated or dispersed soil, but a neutral salt such as NaCl appears ineffective. Because strength development with NaOH requires leaching, adsorbed moisture also is expected to increase, thus offsetting strength gains.

### Organic Chemicals

In general, large organic cations such as Armac T, ethylamine HCl, and hydroxylamine HCl may be suitable for decreasing the expansive properties of soils. However, shear strength improve-

ments appear only when moisture content is low. None of the three compounds seems especially desirable for landslide stabilization at the 5% level of application. Many compounds that are soluble enough to dissolve in water and penetrate landslides also are soluble enough to be leached by rainfall. However, there are thousands of organic compounds. Perhaps one will be found that is soluble in water, has a high affinity for smectite, increases the shear strength at all moisture levels, and is resistant to leaching and biological degradation.

Other aspects of landslide stabilization with organic chemicals were not investigated, but one approach, in particular, needs further investigation. This involves changing the permeability of the soil surface. For example, coarse, noncohesive soils can produce landslides only after rapid penetration of rainfall. Anything that reduces the infiltration rate, such as a thin film of an organic chemical, might be of use in preventing landslides in certain soils, provided lateral seepage is prevented.

### Phosphates

The acidic phosphates form insoluble iron and aluminum precipitates that act as cementing agents in soils. The neutral salt, diammonium phosphate, behaves much like other soluble salts. First, there is an increase in strength at low moisture levels, and then, after leaching, an increase in strength at high moisture levels. The latter development occurs at the expense of strength at low moisture levels. However, when acidified calcium phosphate was added to Diablo clay, cementing agents formed. This treatment, as well as the treatment with phosphoric acid alone, increased shear strength at moisture contents below 60%. Subsequent neutralizing and leaching further enhanced this strength development. Therefore, the acidic phosphates show promise for landslide stabilization in which permanence is a major factor.

### Sulfates

Aluminum sulfate increased the shear strength of Diablo clay at low moisture levels. Ammonium sulfate produced only marginal and temporary increases in shear strength. Calcium sulfate produced no significant change in physical properties. Ferrous sulfate doubled the liquid limit and increased the shear strength at high moisture levels after the neutralizing and leaching step. Incidentally, these changes were not nearly as great when the soil was air dried prior to neutralizing and leaching. This demonstrated that the oxidation of iron from the ferrous to the ferric state could affect the measurement of the physical properties of certain iron-rich soils that are normally found in a reduced state beneath the water table. In order to get values applicable to the natural state, such soils should not be air dried prior to testing.

The ferrous sulfate treatment also was performed on a non-expansive clay mineral, kaolinite. The failure of this treatment of kaolinite to produce dramatic increases in LL and shear strength showed that ferrous sulfate treatment produces such dramatic increases only in soils in which ferrous hydroxide can precipitate between the layers of an expansive clay. The smectite in the test soil, Diablo clay, is such an expansive clay.

Sulfuric acid increased shear strength at low moisture levels. However, this effect was noticed only after the neutralizing and leaching step. The insolubility of ferric sulfate in sulfuric acid may be responsible for some of the effectiveness of sulfuric acid.



## Other Chemicals

Sodium metasilicate produced large increases in the liquid limit and in shear strength at all moisture contents. This improved strength persisted after leaching. Metasilicates should be investigated for changes in soil permeability that might increase the moisture contents of landslides.

Potassium iodide does not appear useful for stabilizing smectitic landslides. Soil treated with a mixture of calcium hydroxide and ferrous sulfate was dominated by calcium hydroxide. Shear strength was improved at low moisture levels. The ferrous sulfate prevented the decreases in expansion normally achieved with calcium hydroxide treatment.

Ferric oxide essentially did not change the physical properties of Diablo clay. Iron powder slightly increased the shear strength at all moisture levels. Thus, the formation of iron compounds other than ferric oxide appears to produce minor increases in shear strength.

Aluminum nitrate reduced the LL without reducing the shear strength significantly. After neutralizing and leaching, the aluminum nitrate-treated soil displayed a tremendous increase in LL. There were corresponding increases in shear strength at high moisture levels. Most likely these results were produced by aluminum hydroxy interlayer formation in smectites, a reaction which, as noted above, was responsible for significant strength gains from treatments with ferrous iron and other aluminum systems.

## THEORY

### Mechanics of Landslides

Only certain types of landslides may be amenable to chemical stabilization. These include landslides occurring in soils and sedimentary rocks having significant amounts of clay minerals that adsorb large quantities of water at very slow rates. An increase in the water content of such a soil causes it to lose shear strength. Water-saturated soil of this kind on a slope can thus lose the resistance to the force of gravity necessary to maintain the slope. The resulting landslide generally develops along a slide plane consisting of laminated clay. A slide plane may develop when the overburden pressure exceeds the shear resistance. If the slide plane is the only area of movement between stable and unstable materials, an improvement in the shear strength of clay in this zone will at least temporarily stop the slide. The addition of more water may, of course, start the slide moving again by increasing its weight and decreasing the shear strength.

Arora and Scott (1974) maintain that slide planes are natural drainage ways within a slide. They say that chemicals added to slide planes and cracks near the headwall of a slide will diffuse along the slide plane changing the shear strength as they go. An alternate method of introducing chemicals into a slide plane is to drill a hole until the slide plane is contacted, then fill the hole with chemical solution that subsequently diffuses throughout the slide plane. If many slide planes are developing throughout a slide or if the clays tend to be thixotropic, many boreholes are drilled and chemicals are kept in contact with these holes until the entire mass of the slide has been exposed to them. The amount of water included with such treatments is usually an insignificant proportion of the amount already in the slide and does not reduce the shear strength appreciably.

## Chemical Reactions with Soils

Murray (1952) pointed out that no one chemical is likely to be suitable for stabilizing all soils. This can be more greatly appreciated by reviewing some 18 possible changes that might result from adding a chemical to a soil. According to Arora and Scott (1974), these reactions include:

1. Exchange of cations
2. Exchange of anions
3. Adsorption
4. Fixation
5. Formation of new minerals
6. Cementation
7. Salt conversion
8. Modification of water films
9. Adsorption of water films
10. Enrichment of pore water with ions
11. Modification of capillary forces
12. Modification of the electrical surface tension of clay minerals
13. Modification of the electrical forces between particles
14. Modification of chemically bound water
15. Adsorption of chemically bound water
16. Neutralization of acids
17. Neutralization of bases
18. Proton exchange

Of these reactions, the first six appear to be the most important. Reactions 7 to 13 probably occur each time a chemical is added to a soil. However, they are likely to be affected by subsequent leaching of soil pore solutions during rainfall. Landslides stabilized by these reactions are therefore likely to be reactivated after the chemical leaches away. Reactions 14 to 18 are especially complicated and probably would be unique for each soil.

Cation and anion exchange will be discussed under *ion exchange*. Adsorption and fixation will be discussed under *formation of interlayers in expansive clays*. Cementation and new compound formation will be discussed under the *formation of insoluble cementing agents*.

### ION EXCHANGE

Ion exchange is a well-known mechanism alluded to in advertising by Ion Tech, Inc., of Daly City, California, a company that formerly specialized in stopping landslides with chemical treatment. It is also the primary emphasis of the article by Arora and Scott (1974). Cation exchange is much more important than anion exchange in expanding clays such as smectite (Borchardt, 1977a). The double layer theory (Babcock, 1963) can be used to explain the results of replacing monovalent or divalent cations with cations of higher charge. Supposedly, the higher the charge on the cations attached to the clay, the greater will be the shear strength.

The extent to which cation exchange can occur in a soil is dependent on factors that include the type and amount of clay and natural cations present, as well as the type and amount of cations added to the soil. For example, 5 g of NaCl will replace only 10% of the  $\text{Ca}^{2+}$  on 100 g of Ca-montmorillonite, but 5 g of KCl will replace about 20% of the Ca (Carroll, 1959). Salts with divalent cations, such as  $\text{MgCl}_2$ , would replace more than 40% of the  $\text{Ca}^{2+}$ . Salts with trivalent cations, such as  $\text{AlCl}_3$ ,

would replace considerably more than half of the  $\text{Ca}^{2+}$  from pure montmorillonite. Trivalent cations, such as  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$ , would therefore, be preferred for stabilization through cation exchange.

#### FORMATION OF INTERLAYERS IN EXPANSIVE CLAYS

Adsorption and fixation of most chemical compounds in smectites involves "interlayer formation." Either organic or inorganic cations or molecules can enter the space between adjacent layers of expanding layer silicates. When these layers collapse, the material trapped between them is considered to be either "fixed" or "adsorbed." When the material can not be removed by simple cation exchange, it is generally called an "interlayer."

Aluminum, iron, magnesium, and other metallic elements form hydroxides capable of producing interlayers in expanding clay lattices (Caillere and Henin, 1949; Carstea, Harward, and Knox, 1970a, 1970b, 1970c). Polymerization of these metallic hydroxides can inhibit expansion and collapse of clay minerals such as montmorillonite and vermiculite. This results in a "chlorite-like" mineral, and the process is appropriately called "chloritization." Chloritization occurs naturally in acid soils (pH 5) and would be expected to modify those clay properties related to landslide potential.

Diffusion of metallic cations through the soil at low pH should be more rapid than diffusion of polymerized hydroxides of the same metals. An ideal, two-step procedure would involve diffusion of metal ions through the soil followed by the addition of a soluble hydroxide solution to convert simple ion exchange into a more permanent interlayer formation. This process was tested by adding ammonium hydroxide to soils previously treated with acidic chemicals.

#### FORMATION OF INSOLUBLE CEMENTING AGENTS

Soil particles commonly are held together by oxides and hydrous oxides of aluminum, iron, and silica (Russell, 1961). The formation of additional insoluble materials or new minerals within the soil would be expected to increase the shear resistance. A chemical soluble enough to diffuse through the soil would have to react with the soil in some way in order to precipitate an insoluble cementing agent. The large variation in mineralogy and chemical composition of soils tends to increase the number of reactions and products that could form. Not all of these may be beneficial for landslide stabilization.

### Shear Strength and Permeability

The permeability of a soil can be increased more than 100% or decreased 99% through chemical action (Arora and Scott, 1974). Sodium-saturated soils are noted for their impermeable nature. The addition of gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ , to such salt-affected soils is one of the most common ion exchange reactions used in agriculture (Russell, 1961). Soluble salts of divalent metals increase soil permeability when applied to sodium-affected soils.

Quirk and Schofield (1955) state that there are three processes operative in decreasing soil permeability: (1) blockage of large conducting pores through soil swelling; (2) failure of soil aggregates produced by unequal stress due to swelling; and (3) deflocculation of clay as salt concentrations decrease and the charged clay platelets move apart during swelling. In this connection, Arora and Scott (1974) state that "actual laboratory studies show that there is no direct correlation between floccula-

tion and strength characteristics." If this is true, there is also no direct correlation between soil permeability and strength characteristics.

Landslides may occur when the rate of water addition into an already wet soil is greater than the rate of water drainage. A chemical treatment that increases permeability without increasing shear strength at the same time may result in removal of water from a slide if free drainage is provided. Removal of water, of course, would strengthen the soil's resistance to shear. Permeability, therefore, is possibly as important a factor in chemical stabilization of landslides as shear strength and moisture content. In general, this study does not address itself to the question of permeability, which should be a topic for further research on the chemical stabilization of landslides.

### Hypothetical Changes in Physical Properties

#### SHEAR STRENGTH

In applying chemicals to landslides for the purpose of increasing the shear strength, our aim will be to bring about either (1) reductions in water content or (2) increases in strength at constant water content. The torsion vane is convenient for determining shear strength at any particular water content. By plotting the percentage of water against the logarithm of the shear strength, a straight line is obtained (Kerr and Drew, 1969; Borchardt, 1977b). Such a determination was made for untreated Diablo clay and is represented by the curve labeled "CONTROL" in the figures. Curves determined on chemically treated samples show an improvement in shear strength when they lie above this CONTROL curve and a decrease in strength when they are below it.

Theoretically, a chemical treatment could affect the location of the shear curve in one of only eight ways (Figures 1a through 1d). Each curve can be defined by only two variables, the intercept and the slope. Air-dried Diablo clay had 10% water, and this is considered a more practical intercept than 0% water (oven dried for 24 hours at 110°C). The other variable, slope, appears to be highest for soils having the properties of expanding clay (Borchardt, 1977b). For example, silty and sandy materials give curves similar to type A and clayey, montmorillonitic soils give type B curves (Figure 1a). In the following discussions, it is assumed that the steepness of these shear curves is related to cohesion and that the intercept is related to internal friction, the other component of shear strength.

Increases and decreases in intercepts and slopes all refer to changes that would occur in the control sample if it were treated chemically. Hypothetical possibilities are as follows:

*Variation in slope without change in dry strength: Curve types A and B.* Curve type A (Figure 1a) illustrates a decrease in shear strength at all moisture contents with the effect greatest at high moisture contents. Type B illustrates an increase in strength at all moisture contents. Both curves show the same dry strength as the control, but cohesion may have been reduced in type A and increased in type B.

*Variation in slope with an increase in dry strength: Curve types C and D.* Curve type C (Figure 1b) is typical of a chemical treatment in which shear strengths are reduced at high moisture contents but increased at low moisture. Curve type D shows a large increase in cohesion and dry strength, and, therefore, an increase in shear strength at all moisture contents.



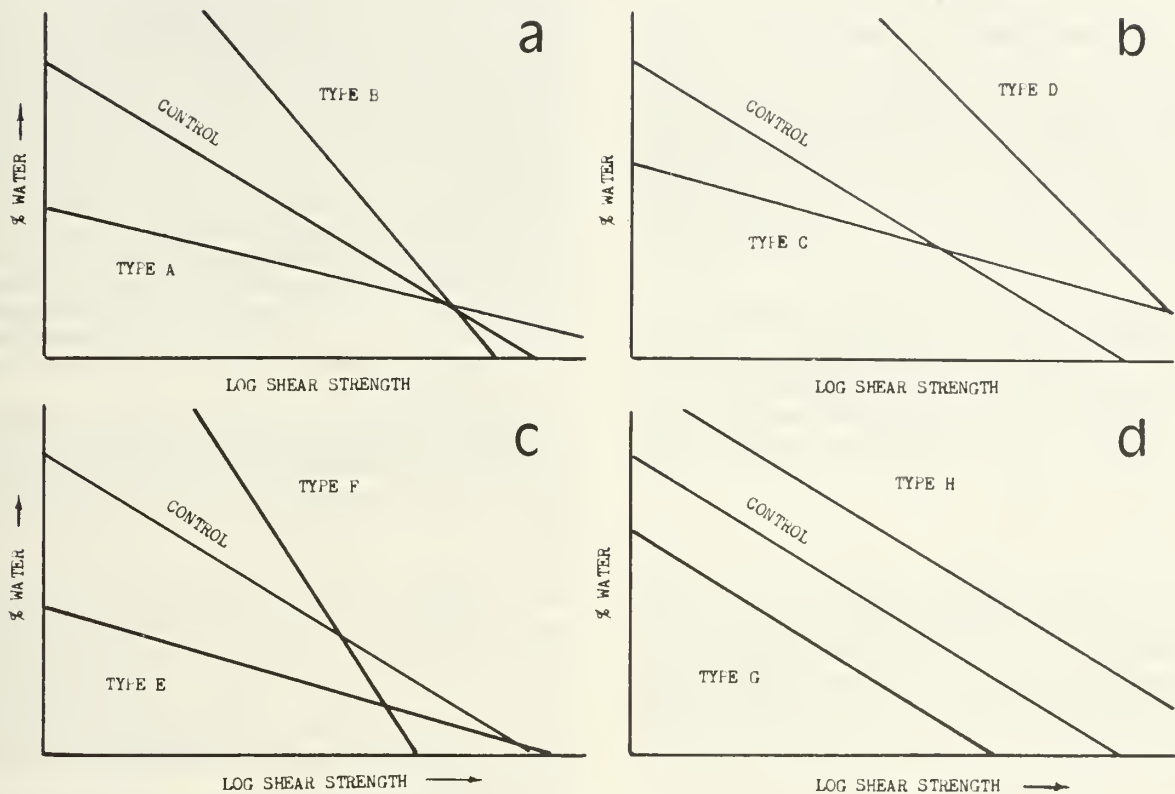


Figure 1. Hypothetical shear curves resulting from chemical treatment of soil

*Variation in slope with a decrease in dry strength: Curve types E and F.* Curve type E (Figure 1c) shows a loss in strength at all moisture contents; curve type F shows increases in strength at high moisture contents and decreases in strength at low moisture contents.

*Variation in dry strength without change in slope: Curve types G and H.* Curve type G (Figure 1d) shows a loss in strength at all moisture contents while curve type H shows a gain in strength at all moisture contents. Both curves show the steep slopes typical of the original montmorillonitic soil. Perhaps internal friction is greater in type H than in type G curves.

In this study, type C curves were a common result of chemical treatment with soluble salts such as NaCl. Subsequent neutralization of soil treated with certain acid salts, such as  $\text{AlCl}_3$ , resulted in conversion of type C to type B or F curves. Treatment with KF produced a type D curve, but HF produced a type H curve, and  $\text{FeCl}_3$  produced a type G curve. A type E curve was not observed. An ideal result of chemical treatment would be curves H or D, in which shear strengths are increased at all moisture contents. Chemicals that produce less than ideal results should be used with caution, but those producing type E or G curves should not be used on landslides unless it can be shown that improved drainage will offset decreases in shear strength.

#### LIQUID LIMIT

Arora and Scott (1974) maintain that it is impossible to affect engineering behavior of soils without a change in the Atterberg limits (that is, the liquid limit and the plastic limit). High liquid limits are directly related to the amount of expanding smectite clay in a soil ( $r=0.77$ ) (Borchardt, 1977b). The liquid limit (LL) is also very sensitive to the type of cation saturating the clay. For example, sodium-saturated Wyoming montmorillonite (a smectite group mineral) had an LL of 700 whereas the same clay saturated with calcium had an LL of 157 (Mielenz and King, 1955, p. 220). Double-layer theory predicts that sodium-saturated montmorillonite will have a much larger separation of the clay layers than calcium-saturated clay (Babcock, 1963). Large separations allow more water between layers than small separations. This means that, in sodium-saturated montmorillonite, a high water content must be reached before the change (that defines the LL) from plastic to liquid flow can occur. The liquid limit is thus an indirect measure of the distance between clay layers.

Double-layer theory also predicts that increasing the salt concentration in the pore solution of a clay-water mixture should reduce the distance between clay layers. Collapse of these layers, then, would be exhibited as a decrease in the LL. Likewise, a decrease in salt concentration through leaching would increase the LL.

The amount and source of negative charge may affect the expansion of clay (Borchardt, 1977a). Theoretically, any changes in the amount of this charge could, therefore, affect the LL. Permanent attachment of small amounts of positively charged, hydroxy interlayers would reduce the negative charge of a smectite. Large amounts of such an interlayer might bind clay layers together and thus prevent expansion in the same way naturally occurring interlayers prevent the expansion of chlorite. Another mechanism for layer-charge reduction might include entry of small cations such as  $\text{Li}^+$  into empty octahedral positions (Green-Kelly, 1953). Still another, is the protonization of oxygen atoms in the lattice (Raman and Jackson, 1966).

It is not entirely clear how a change in LL might affect the landslide potential of a soil. Chemical treatments that increase the LL usually increase the shear strength and expansivity as well. An increase in LL would naturally increase the amount of water a soil could hold before sliding. A decrease in LL might trigger a slide unless a corresponding increase in natural drainage or permeability occurs.

### PLASTIC LIMIT

The plastic limit (PL) appears unrelated to the liquid limit, clay content, smectite content, or shear strength (Borchardt, 1977b). Soils with large amounts of organic matter have high plastic limits, mostly due to the high water-holding capacity of organic matter. Any chemical-soil interaction that tends to prevent plastic flow would raise the PL. Also, a hydrated chemical would increase the LL and the PL to whatever degree it lost water at  $110^\circ\text{C}$ .

### Weathering

Rainfall tends to remove soluble salts from soils. Laboratory leaching simulates this process, though it would occur more slowly in the field. Lyons, McEwan, and Siebenthal (1962) noted an increase in pH with time in soils treated with phosphoric acid. Through time, the natural buffering capacity of a soil would decrease the pH of an alkali-treated soil and increase the pH of an acid-treated soil. This process was simulated by neutralizing the soil with base or acid followed by leaching to remove the soluble reaction products. This allowed an assessment of the probable long-term effects of weathering upon landslides treated with chemicals.

### ASSUMPTIONS

The interpretations of these data depend in varying degrees upon the correctness of the following assumptions. Each assumption, therefore, is subject to further testing and verification.

(1) *Shear strength is a log function of the water content of chemically treated soils.* This has been asserted for untreated soils (Casagrande, 1932; Winterkorn and Moorman, 1941; Kerr and Drew, 1969), but is it true after chemical treatment? For illustrative purposes, shear curve data have been extrapolated to moisture contents above the liquid limit and below the plastic limit.

(2) *Chemical treatments may affect the measured shear strength at the liquid limit.* This assumption appears to contradict the generally accepted statement by Winterkorn and Moorman (1941) that "Soils at the liquid limit can be considered as of equal, though small, shear resistance." Data points for LL and PL have been placed on extrapolated curves for shear strength. Some shear strength values for LL vary so much from the con-

trol value ( $0.022 \text{ kg/m}^2$ ) that the assumption appears supported. This points out the limitations of the original assumption of equal density for all soils (Casagrande, 1932). That assumption is not completely valid for liquid limit tests of chemically treated soils. Decreases in soil density are produced by increases in water contents when clay minerals expand or gels form. This results in a high LL that would plot at a low shear strength. On the other hand, increases in soil density might be produced by collapsed clay minerals and dissolved salts. These LL values would be slightly low and would plot at a high shear strength.

(3) *Neutralization with ammonium hydroxide or hydrochloric acid simulates a likely result of soil weathering.* These treatments are an extremely simplified way of viewing a very complicated process. The treatments merely suggest trends that must be considered before stabilization is attempted with acidic or basic compounds.

(4) *Laboratory leaching simulates leaching by rainfall.* This assumption generally is supported by numerous studies in soil fertility. Because soil leaching is studied best as a rate process, much more elaborate experiments usually involve soil columns (Chao, Harward, and Fang, 1962) instead of the beakers used here.

(5) *Increasing shear strength at all moisture contents is a desirable objective of chemical stabilization of landslides.* This may be a good, short-range objective, but is it likely to be a permanent solution to a landslide problem? The answer to this depends upon corresponding decreases in soil permeability and increases in water holding capacity that might offset gains in strength. At the very least, an increase in shear strength may allow enough time to enable one to intercept or divert further rainfall from the slide area.

(6) *Remoulded shear strengths measured with the torsion vane present an adequate picture of field conditions.* When a soil is remoulded, soil structure is destroyed and many bonds between larger particles are broken. This causes the measured shear strengths to be lower than they would otherwise be. The pessimistic view on evaluation of chemicals for soil stabilization has been expressed by Barenberg (1963): "The criteria and test procedures which are used to measure effectiveness of a stabilizing agent are arbitrary and in no way related to the service conditions of the stabilized soil in the field." Even so, remoulded shear strengths would appear to give at least minimum values for strength showing trends that can be studied further with more elaborate equipment.

(7) *One soil, Diablo clay, can represent a significant number of cohesive landslides that could be stabilized with chemicals.* It is generally accepted that the physical properties of cohesive landslides result from the presence of clay minerals—especially the expansible clays such as montmorillonite and beidellite. Diablo clay contains a significantly high percentage of these minerals, along with other clay minerals that are likely to be present in other cohesive landslides (Table 1). Only a few aspects of the data for Diablo clay would be useful for non-smectitic landslides, such as the quick clays of Scandinavia and Canada.

(8) *The 5% concentration level (5 g chemical/100 g dry soil) is optimum for testing the effects of chemicals on Diablo clay.* Optimum concentrations probably are different for each chemical and each soil. However, 5% appears to be the most common level used for lime stabilization. Levels greater than 5% are likely to be less economical and less practical, and in some instances those greater than 5% are counterproductive. In most cases, levels less than 5% were tested indirectly by leaching the soil of unreacted chemicals. Leached samples tend to show some of the physical properties that might be expected of soils with low concentrations of chemicals.



(9) *Soluble chemicals diffuse through the soil fast enough to stabilize smectitic landslides.* The rate of diffusion is likely to be different for each chemical and each soil. Highly soluble salts, such as the chlorides, move into dry landslide materials at least as fast as the transport medium. When a landslide already has a high water content, the soluble salt moves by diffusion from areas of high concentration to areas of low concentration. The greater the salt concentration in a soil, the greater is its permeability (Quirk and Schofield, 1955). Thus, precipitation entering a chemically-treated landslide will move rapidly through areas of excess salt concentration, picking up salts and slowly spreading them through untreated areas. This rate of movement would be extremely slow for chemical compounds of low solubility or with a tendency to react with the soil so fast that they precipitate at the point of application.

**Table 1.** *Physical, chemical, and mineralogical properties of the experimental soil, Diablo clay (CDMG No. 485/72).*

Physical Properties	%
Sand (2 mm-63 $\mu$ m)	1.3
Silt (63 - 2 $\mu$ m)	48.7
Clay (<2 - $\mu$ m)	50.0
Liquid limit (LL)	86
Plastic limit (PL)	21
Plasticity index (PI)	65
Air dry moisture content	10
Field moisture content	10-40
Chemical Properties	meq/100 g
Extractable Ca <sup>1</sup>	23.5
Extractable Mg <sup>1</sup>	26.8
Extractable Na <sup>1</sup>	6.8
Extractable K <sup>1</sup>	0.9
Total extractable bases <sup>1</sup>	57.9
Cation exchange capacity of soil (<2 mm)	57.7
Cation exchange capacity of clay (<2 $\mu$ m)	94.4
pH (paste method)	7.4
Calcium carbonate	0.05%
Mineralogical Properties of the Clay Fraction	
X-ray diffraction	Montmorillonite-abundant Beidellite-moderate Mica-trace
Quantitative clay mineralogy <sup>2</sup>	%
Smectite	43
Vermiculite	23
Mica	21
Kaolinite <sup>3</sup>	20
Noncrystalline material	8
Total	115

<sup>1</sup> Analysis by W. Dennis Nettleton, Research Soil Scientist, National Soil Survey Laboratory, Soil Conservation Service, U.S.D.A., Lincoln, NE.

<sup>2</sup> By the methods and definitions of Alexiades and Jackson (1966).

<sup>3</sup> This probably includes much Fe-smectite rather than kaolinite, thus producing a total greater than 100%. There is little x-ray evidence for 20% kaolinite (Figure 2).

## MATERIALS

### The Test Soil: Diablo Clay

In this study, the effect of chemicals on cohesive landslides that contain expansive clay minerals was of particular interest. Expansive clays, such as smectite, were needed to test the three chemical reactions expected: (1) ion exchange; (2) interlayer formation; and (3) cementation. Most non-cohesive landslides do not contain significant expansive clay. Also, such landslides can be avoided more easily by preventing rapid infiltration of water.

Only one soil was selected because of the large number of chemicals to be tested. This soil, Diablo clay, is one of the most expansive and landslide-prone to be found in a group of 66 landslide samples from coastal California (Borchardt, 1977b). The experimental soil (CDMG no. 485/72) is from the C horizon (relatively unweathered Miocene shale) of Diablo clay at a site located in a gully near Leisure Lane south of El Sobrante in Contra Costa County, California (latitude 37°57.40'N and longitude 122°17.44'W). The material is a light olive gray (5Y6/2d, 5/3m), silty clay from the 157-167 cm depth interval. A large quantity of soil was collected, air dried, and split into representative 110 g portions. The weight of these portions would have been 100 g if they had been oven dried before testing.

The test soil is about half clay and half silt (Table 1). It has a liquid limit of 86 and a plastic limit of 21, resulting in a very high plasticity index of 65. The pH is nearly neutral at 7.4.

Extractable bases were dominated by Mg (26.8 meq/100 g) rather than Ca (23.5 meq/100 g). Extractable Na was about 12% of the cation exchange capacity (Table 1).

X-ray diffraction showed abundant montmorillonite, moderate beidellite, and a trace of mica in the clay fraction (Figure 2). The high liquid limit and plasticity index results from the expansive nature of montmorillonite and beidellite. The silt fraction is mostly quartz and feldspar.

## Chemicals

Chemicals were of reagent grade purity. It was necessary to weigh out more than five-gram quantities of certain hydrated salts (for example, FeSO<sub>4</sub>·6H<sub>2</sub>O) in order to get the five grams of unhydrated equivalent (FeSO<sub>4</sub>).

## METHODS

Two important parameters must be measured to predict imminent slippage of a landslide-prone soil: the shear strength and the water content. It seemed pertinent, therefore, to study the relationship between these two parameters for use in monitoring the effects of a chemical treatment in stabilizing soils prone to landslides. Any change in the intercept or slope of a shear strength curve would result from the effects of chemical reactions within the soil.

### Shear Strength with the Torsion Vane

A torsion vane (Soiltest, Evanston IL) was used to determine shear strength at various moisture contents between the liquid and plastic limits. These shear tests were run in conjunction with those for the Atterberg limits. Samples were allowed to dry slightly after soil was removed for the liquid limit test. A torsion vane reading was made directly in the liquid limit device after thorough mixing. About 10 grams of soil from the area of shear was placed into a tared weighing bottle and oven dried at 110°C

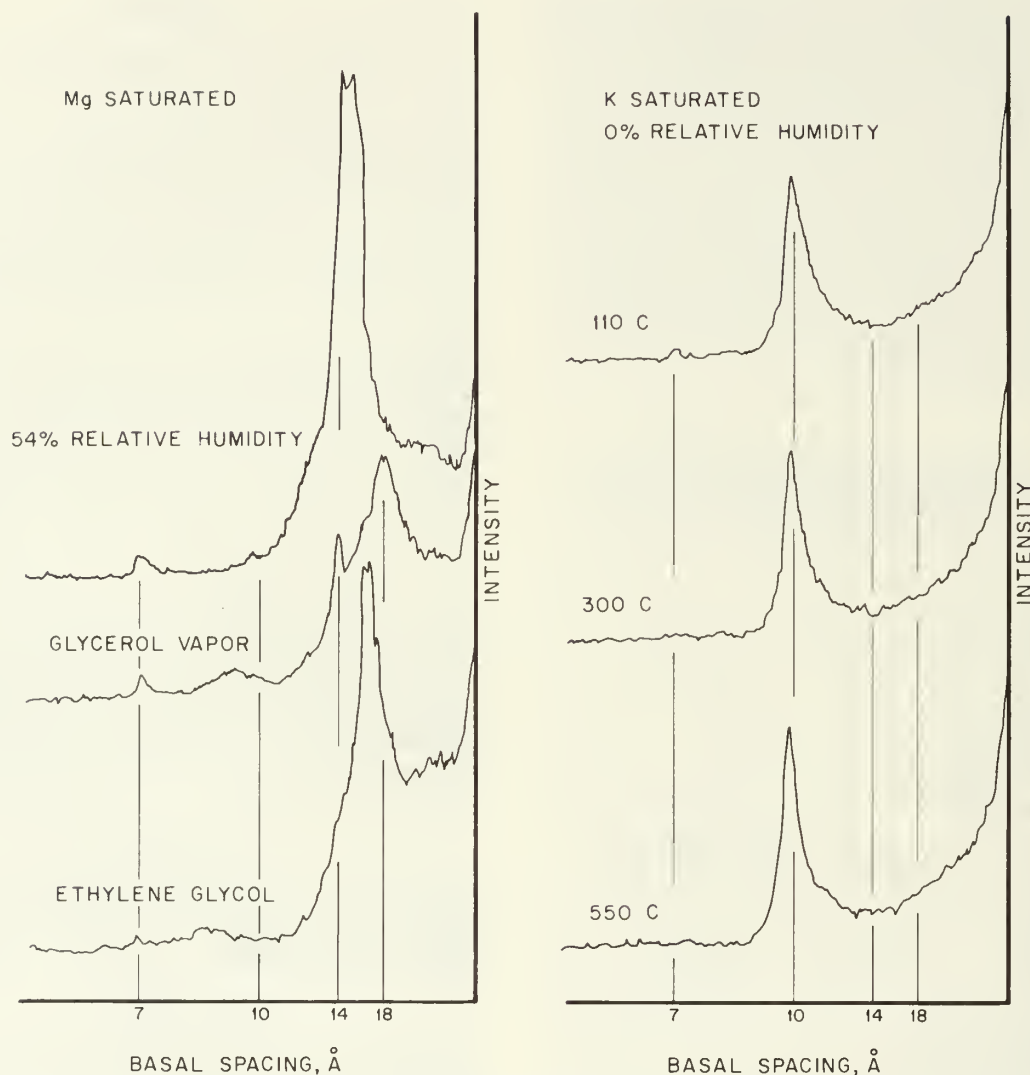


Figure 2. X-ray diffraction patterns of Diablo clay showing predominant montmorillonite and beidellite (less than 2  $\mu$ m fraction)

to determine moisture content. This was repeated for a duplicate analysis, and then the entire soil sample was dried with a fan blower while being mixed. At some point prior to reaching the plastic limit, two more torsion vane readings and moisture determinations were made. The results were plotted on a graph of percent  $H_2O$  versus the log of the shear strength in kilograms per square centimeter (see, for example, Figure 3). Preliminary results (Borchardt, 1977b), as well as the work of others (Kerr and Drew, 1969), indicated a linear logarithmic relationship between these points. Precision of the method (1-3%) appears to be sufficient for the use of only two to four points to establish the shear curve (Borchardt, 1977b).

These shear curves enable one to tell at a glance what changes in strength have occurred as a result of chemical treatment. They also emphasize that shear strength is a dynamic function of soil moisture—a property that continually changes in the field depending on the season.

Soils with high proportions of expansive clays tend to have shear curves with high intercepts on the y-axis and high negative slopes. Shear curves for non-expansive clays, silts, and sands have low intercepts and low negative slopes. Under conditions of restricted drainage, a small increase in moisture causes a larger decrease in shear strength for non-expansive clays, silts, and sands than it does for expansive clays.

### Atterberg Limits and Particle Size Distribution

Liquid limits, plastic limits, and plasticity indices were determined by using standard methods (Sowers, 1965; Borchardt, 1977b and 1977c). Particle size distribution was determined by using the hydrometer method with sodium metasilicate dispersion (Borchardt, 1977b and 1977c).

## Extractable Bases and Cation Exchange Capacity

The National Soil Survey Laboratory measured the extractable bases by using the standard ammonium acetate procedure (Table 1). For this soil, the extractable bases are equivalent to the exchangeable cations that naturally occur on the clay. The cation exchange capacity (CEC) was determined by Division staff by saturating the soil or clay sample with 1*N* CaCl<sub>2</sub>, washing with methanol, and exchanging the Ca with 1*N* NaCl. The exchanged Ca was determined by titration with EDTA (Jackson, 1958, p. 287).

## pH

Equilibrium pH was determined by adding sufficient water to the soil to form a sticky paste (Jackson, 1958). A Beckman Model G pH meter was used, and the suspension pH was measured while stirring as described below.

## Calcium Carbonate

Inorganic carbon, expressed as CaCO<sub>3</sub>, was determined by the method of Bundy and Bremner (1972). Four ml of concentrated HCl was added to dry soil mixed with 20 ml of water in order to decrease the acid injection time.

## Clay Mineralogy

Qualitative analysis of the clay fraction was performed by x-ray diffraction (Borchardt, 1977b and 1977c) (Table 1). Quantitative clay mineralogy was determined by using the methods of Alexiades and Jackson (1966). In summary, these methods use CEC to determine smectite and vermiculite. Total K<sub>2</sub>O (2.10%) content is multiplied by ten to determine mica. Weight loss after boiling the sample in 1*N* KOH is used to calculate noncrystalline material. The latter procedure is repeated after 550°C heating to determine kaolinite.

## Addition of Chemicals

For each treatment, 110 g of air-dry soil (100 g oven-dry equivalent) was added to a 200 ml, tall-form beaker. Appropriate amounts of chemicals (5 g unhydrated equivalents where unspecified) were dissolved in 60 ml of deionized water. Each solution was applied to the surface of the soil and allowed to diffuse to the bottom of the beaker. This generally occurred within 1.5 hours.

Treatments with relatively insoluble chemicals [for example, Ca(OH)<sub>2</sub>] were prepared by using a spatula to mix the dry powdered chemical with the air-dry soil. Then, 60 ml of deionized water was added to the surface of the sample. All samples were then allowed to "age" or "cure" for periods up to 150 days.

Certain chemicals required special handling. Armac T, a fatty acid, had to be mixed with water first and then physically mixed with the soil. Hydrofluoric acid (HF) is extremely dangerous. Rubber gloves were worn and a fume hood was used while handling HF-treated soil. Plastic ware was substituted for glass containers, because HF dissolves glass just as it dissolves siliceous minerals in the soil.

## Soil Neutralization

Many of the materials undergoing chemical treatment were mixed with base or acid to simulate a probable result of weathering. Soils have a great buffering capacity, and they slowly neutralize acidic or basic chemicals with which they come in contact. Ammonium hydroxide and hydrochloric acid were selected for soil neutralization.

The chemically treated soil samples were transferred to 600 ml beakers with about 400 ml of water. The suspension was stirred with a magnetic stirrer while 1*N* HCl or NH<sub>4</sub>OH was added to bring the pH to 7.0. This was repeated each day until neutrality was maintained for 24 hours. The final pH values for "neutralized" samples differed from 7.0 for several reasons: the samples were subsequently leached of excess salts that normally affect pH readings, equilibrium was difficult to achieve and the pH of a soil suspension is always higher than that of a soil paste (Jackson, 1958).

## Soil Leaching

Laboratory leaching of a soil simulates the effects of rainfall on a chemically treated landslide. Obviously, the stabilizing effects of chemicals washed away by rainfall would be short-lived. In general, efforts were made to speed up the process of neutralization. When this process was completed, it was followed by leaching. Actual reactions in the field may not necessarily occur in that order, nor will they occur in so short a time. Indeed, rates of reaction and leaching of chemicals in soils involve separate studies in themselves. Better procedures for evaluating chemical treatments of landslides will no doubt be devised. Early work includes a field investigation of the short-term effects of the chemical treatment of a landslide in California (Mearns and others, 1973).

Chemically treated soils were leached of excess soluble salts by mixing them with 100 to 600 ml additions of distilled water. After the flocculated soil had settled to the bottom, the clear supernatant liquid containing the excess soluble salt was discarded. This was repeated each day (or more often) until the supernatant liquid became cloudy and dispersion of the clay was evident. The suspensions were then evaporated to a paste by drying in a 60°C oven, on a hot plate, or preferably with the aid of a laboratory blower. In the latter case, a heat gun was used to warm the air used for drying. The ammonium phosphate dried out completely on the hot plate, causing a black precipitate to form. In future studies, heating of the soil probably should be avoided.

## REVIEW OF LITERATURE

The chemical stabilization of landslides is closely related to soil stabilization, which has been reviewed by Mielenz and King (1955), Johnson and others (1960), Ingles (1968), Mura and Thornburn (1969), and more recently by Ingles and Metcalf (1972). Most studies of soil stabilization, until recently (Talme, 1968), were concerned largely with converting soils to non-expanding materials capable of supporting roads. Emphasis was on shrink-swell behavior and general physical changes produced by chemical treatment. A few of these studies also indicated likely changes in shear strength that might result. An evaluation of the literature is especially difficult because of the widely varying types of soils, method of adding chemicals, and methods of



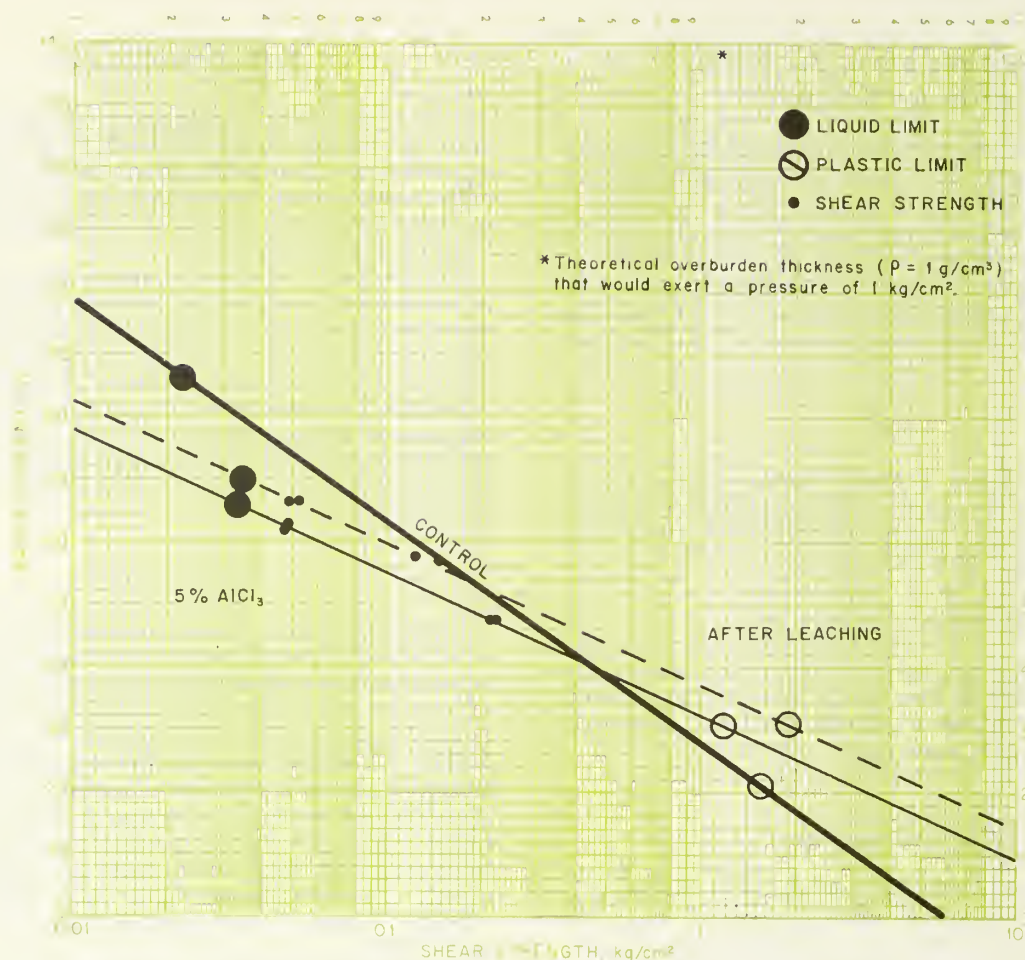


Figure 3. Shear curves for Diablo clay treated with 5% aluminum chloride

evaluating the results. Even when shear-strength measurements are reported, extremely important data, such as moisture contents, often are omitted. Very few of these works consider the effect of soil weathering by performing physical tests after neutralizing or leaching.

### PRESENTATION OF DATA

The literature review and the results and discussion for the experiments reported in the following pages have been organized into seven sections based upon the type of anion dominating the formula of each group of chemicals. Six groups are arranged in alphabetical order: chlorides; fluorides; hydroxides; organic chemicals; phosphates; and sulfates. Within each group, the compounds are discussed in alphabetical order of the cation in the formula. A seventh section includes other chemicals that do not fit any of these groups. Each subsection dealing with a specific chemical treatment begins with a review of the literature pertinent to that chemical's effectiveness as a landslide-stabilizing agent and then proceeds to the test results and their interpretation.

### CHLORIDES

Most chlorides are very soluble. Chloride salts would therefore appear to be ideal for *in situ* application to landslides. Chlorides would be expected to increase the ionic strength of soil solutions and take part in cation exchange reactions. Neutralization of the acidic chlorides, such as aluminum and iron chloride, would be expected to form hydroxy interlayers in expansive clays. The insoluble chlorides would not precipitate in soils because they are so rare. Cementation produced by chlorides, therefore, appears unlikely.

In regard to quick clays, Torrance (1975, p. 333) showed that "In general, all chloride salts cause a significant increase in the liquid limit and the increase is concentration dependent." This contrasts with the results of these investigations with smectitic soil, which show decreases in the liquid limit at high chloride salt concentrations. Quick clays are unique in that they are generally confined to formerly glaciated regions, seldom contain smectite, and usually have natural moisture contents greater than their liquid limits. Most of the work on the effect of chemicals on shear strength involves quick clays and, thus, some of the results below appear to contradict the literature. Even so, the study of

literature on stabilization of quick clay is helpful. In interpreting the results, we will be able to use the double-layer models (Babcock, 1963) that have greater applicability to expansive clay such as smectite than to non-expansive quick clay. Double-layer theory predicts that expanding clays will collapse when salt concentration increases. This causes reductions in the liquid limit that are supported by our data for smectitic soil.

### Aluminum Chloride

*Literature.* Aluminum chloride,  $\text{AlCl}_3$ , doubled the strength of soil after at least two days contact (Kuhn, 1970). Arora and Scott (1974) mentioned aluminum chloride as a source of trivalent cations in their article on chemical stabilization of landslides. Apparently, aluminum chloride has been used successfully in stopping active landslides (Graf and Kuhn, 1970).

Quick clay treated with 0.2% aluminum chloride had three times the strength of clay treated with sodium chloride (Talme, 1968, p. 63). Quick clays treated with 0.27% aluminum chloride increased shear strength from 1.1 to 8.1  $\text{t/m}^2$  (Talme, 1968, p. 72). Doubling the amount of aluminum chloride increased the strength slightly to 9.5  $\text{t/m}^2$  at a constant water content of 78.5%. On the other hand, Dowdy and Larson (1971) found the unconfined compressive strength of Al-montmorillonite to be less than Ca- or Na-montmorillonite at constant water content. Likewise, the liquid limits of Al-smectites (montmorillonite and beidellite) are only slightly less than Ca-smectites and much less than Na-smectites (Mielenz and King, 1955, p. 220).

When aluminum chloride (pH 3) is added to smectitic soil, any increase in pH due to soil buffering, leaching, or artificial neutralization produces hydroxy interlayers in the smectite. Expansive layer silicates, such as smectite, prevent precipitation of a separate  $\text{Al}(\text{OH})_3$  (gibbsite) phase, a process called the "antigibbsite effect" by Jackson (1963).

Even small increases in pH can produce hydroxy aluminum compounds that affect the properties of smectite. For example, the cation exchange capacity of montmorillonite was decreased 25% when added aluminum chloride was brought to pH 5 with sodium hydroxide (Sawhney, 1960).  $\text{Al}(\text{OH})_3$  was the most common ion found in this solution at pH 5. Very high concentrations of aluminum chloride can form nearly complete hydroxy interlayers in montmorillonite (and vermiculite) when titrated with NaOH (Slaughter and Milne, 1960; Carstea, Harward, and

Knox, 1970a, 1970b). These interlayers are stable to heating at 600°C and can permanently affect expansion and collapse of expansive layer silicates. For example, Al hydroxy interlayers reduced the swelling of Na-montmorillonite in NaCl solution (El Rayah and Rowell, 1973).

Under naturally acid conditions of soil weathering (pH 5), soil smectites convert to chlorite and then to kaolinite (both non-expanding clay minerals). Montmorillonite has been converted to kaolinite in the presence of large amounts of Al (15 meq/g) at 220°C (Poncelet and Brindley, 1967). Both Kaolinite and chlorite have lower liquid limits, plasticity indices, and lower shear strength at high-moisture contents than smectites. When kaolinite is present without expansive clays, landslides are infrequent (Borchardt, 1977b). One must also remember that mica pseudomorphs (similar to the mineral called "illite") contain expanding layer silicates such as smectite and vermiculite (Borchardt, Jackson, and Hole, 1966).

*Treatment.* We found that five percent amounts of aluminum chloride reduced shear strength at high-moisture contents (greater than 40%) and increased strength at low-moisture contents (Figure 3). This means there would be no change in shear strength for Diablo clay at 40% moisture, the highest observed in the field (Table 1). For the lowest moisture content observed in the field, 20%, the shear strength would increase from 1.65  $\text{kg/cm}^2$  to 3.40  $\text{kg/cm}^2$  (Figure 3). This is about a two-fold increase in strength, but similar calculations show about a 50% decrease in strength if the soil had been at 60% moisture prior to the treatment. Different workers could come to opposite conclusions about the effects of aluminum chloride if each determined the shear strength at different moisture contents.

The LL and PL also can be plotted on the extrapolated shear curves (Figure 3). Aluminum chloride initially decreased the liquid limit of Diablo clay from 86 to 65. This is in accordance with double-layer theory mentioned previously. A high ionic strength in the soil pore solution causes smectites to collapse, releasing interlayer water to the soil pores. This process, like osmosis, involves movement of water from an area of high water concentration to an area of low water concentration. The process explains why the permeability of a soil increases when the salt concentration of the soil solution increases (Quirk and Schofield, 1955).

Salt increases the rate of water flow from an undrained soil, at least until it is leached away. Mearns and others (1973, p. 6) found a rapid drop in the water level in a landslide as it was being treated with acidic chemicals. Other parts of the slide had increases in the water level. Increases in pore pressures may cause a decrease in shear strength in one part of a slide while drainage from another part may increase strength.

If there are no other interactions with the soil, the liquid limit would increase to normal after the aluminum chloride solution is removed. This phenomenon will be seen later when the effects of NaCl are discussed. In our experiment, the plastic limit increased from 21 to 31. This may have resulted from either increased ionic strength in the pore solution or an exchange of  $\text{Al}^{3+}$  for natural cations. Cation exchange would be the most likely explanation for the increase in plastic limit if the PL does not return to normal after leaching the excess aluminum chloride away.

*Leaching.* When excess aluminum chloride and other exchanged cations were removed by leaching the soil with distilled water, there was a slight increase in shear strength at all moisture contents (Figure 3). The LL increased slightly, as it did to varying degrees in the remaining experiments whenever excess salts were leached from this smectitic soil. The fact that the LL did not return all the way to normal indicates that other interactions have occurred in the soil. As mentioned previously, the most likely reaction would involve exchange of the natural cations, such as  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  with  $\text{Al}^{3+}$ . This is likely because the pH of the soil remained low after leaching (pH 3.9), reflecting at least partial aluminum saturation. The natural soil had a pH of 7.4 (Table 1).

*Neutralizing.* A different sample of aluminum chloride-treated soil was neutralized to pH 7 prior to the leaching step. This resulted in a tremendous increase in LL to a value of 107 (Figure 4). Contrary to what might be expected, the interlayer formation resulting from hydroxylation of the Al produced an increase—not a decrease—in soil expansion.



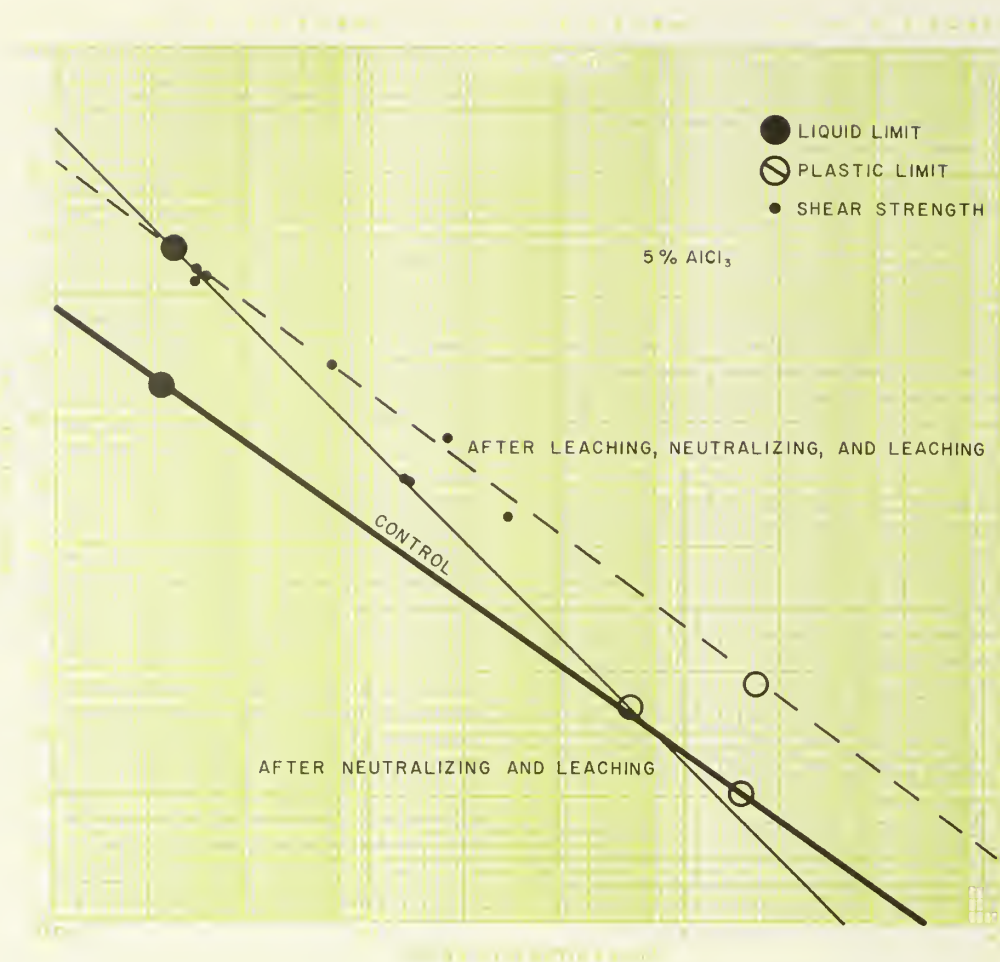


Figure 4. Shear curves for Diablo clay treated with 5% aluminum chloride and neutralized with ammonium hydroxide

Perhaps this result can be explained on the basis of hydroxy aluminum forming external to the smectite structure. Loken (1970) found that 1%  $\text{Al}(\text{OH})_3$  was more effective than  $\text{Al}^{3+}$  in increasing the LL of quick clay. In our experiment, 97 meq of  $\text{NH}_4\text{OH}$  was required to neutralize the soil suspension containing 113 meq of aluminum chloride. The final pH of this soil was 6.1 after the suspension was evaporated to a paste. The titrated form of Al was therefore more like  $\text{Al}(\text{OH})_{2.6}^{0.4+}$  rather than  $\text{Al}(\text{OH})_3$ .

An additional experiment along this line involved leaching the excess aluminum chloride from the treated soil prior to the neutralization step (Figure 4). Most of the exchangeable  $\text{Al}^{3+}$  in the soil occurs between the smectite layers, and the formation of interlayers now appears less ambiguous. The excess hydroxy aluminum in soil pores apparently masked the ability of interlayers to increase shear strength at low as well as high moisture contents.

The plastic limits increased from 21 to 31 or more and remained high during these experiments. The LL and the shear strength at high moisture increased during the experiments simulating the effects of weathering.

*Time.* The effect of time was studied by measuring the physical properties of aluminum chloride-treated clay after one hour, one month, and three months of contact in a 100% relative humidity chamber (Figure 5). These experiments indicate that the initial improvements in low-moisture strength are not permanent. Unfortunately, the assumption concerning the log linearity of shear curves is crucial here because it is difficult to obtain shear strength data at low moisture contents (Figure 5). Nevertheless, the tendency for low-moisture strength to decrease and high-moisture strength to increase through time was clear after three months contact. The increase in LL from 70 to 80 apparently is related to the increases in pH caused by natural buffering in the soil. Perhaps the added Al has continued to hydroxylate and polymerize, thus increasing the LL. This result is similar to that with artificial neutralization and leaching (Figure 3).

The aluminum chloride-soil system is tremendously complicated by the large number of variables that affect hydroxy-aluminum formation in soils. There are unlimited possibilities for varying the amounts and types of Al compounds as well as the amounts and types of hydroxides that can be added at varying rates of speed. For example,  $\text{Al}(\text{OH})^{2+}$  can be prepared by



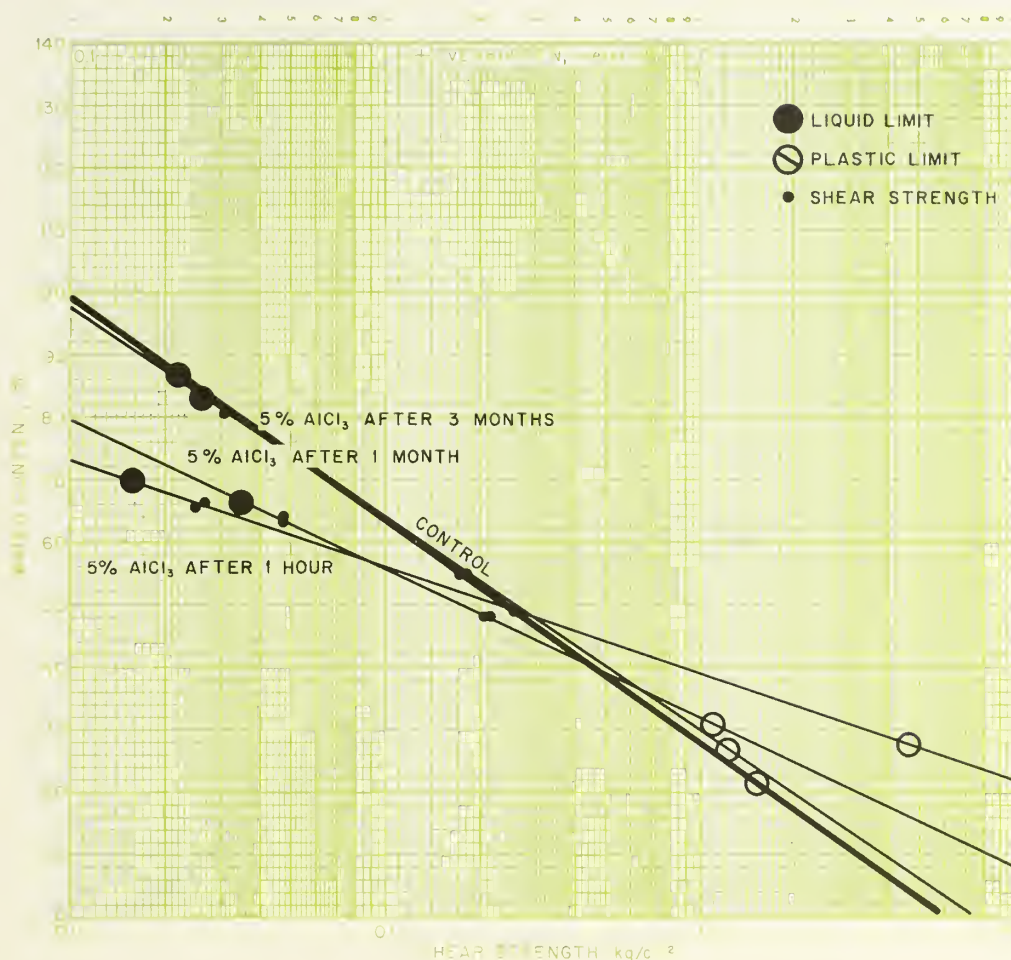


Figure 5. Shear curves for Diablo clay treated with 5% aluminum chloride after one hour, one month, and three months of contact

slow addition of NaOH to aluminum nitrate. This can then be used to interlayer montmorillonite and vermiculite (Dixon and others, 1970). We have shown that several of these variables affect the results rather easily, and that initial results are often temporary.

### Ammonium Chloride

**Literature.** Apparently, this is the first time ammonium chloride,  $\text{NH}_4\text{Cl}$ , has been tested for its effect on soil strength. It was expected to have an effect similar to that of potassium chloride, which has an almost identical power to exchange divalent cations from smectites (Carroll, 1959).

**Treatment.** As it turned out, ammonium chloride decreased the LL of Diablo clay from 86 to 60 (Figure 6). It also increased the PL from 21 to 39. Like aluminum chloride and other salts, ammonium chloride reduced the plasticity index (PI). In this case, the PI dropped from 65 to 21, a decrease in expansivity that is on a par with that produced by the lime treatment, which is commonly used for that purpose.

In general, the plasticity index of a soil is related to the potential volume change (Pettry and Rich, 1971). This relation is

uncertain when chemicals are added to the soil. Salts, such as ammonium chloride, no doubt require a certain amount of water before they will allow a soil to become plastic. The hydration qualities of each salt are different. The special hydration qualities of ammonium chloride could be responsible for some of the increases in PL and LL.

**Leaching.** When excess ammonium chloride was removed, the LL of Diablo clay increased to 96, a value greater than for the untreated soil (Figure 6). This probably reflects the exchange of  $\text{NH}_4^+$  for naturally occurring  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  (Figure 6). The ammonium cation has many properties in common with potassium. K-saturated montmorillonite had an LL higher than Ca- or Mg-montmorillonite (Mielenz and King, 1955, p. 220). In any case, the data indicate that a cation exchange reaction occurred and that ammonium chloride increased the shear strength slightly after the excess salt was leached away.

### Calcium Chloride

**Literature.** There are conflicting data for the effects of calcium chloride,  $\text{CaCl}_2$ , treatment of soils. According to Ingles (1968), calcium chloride produces no change in soil strength. Kuhn

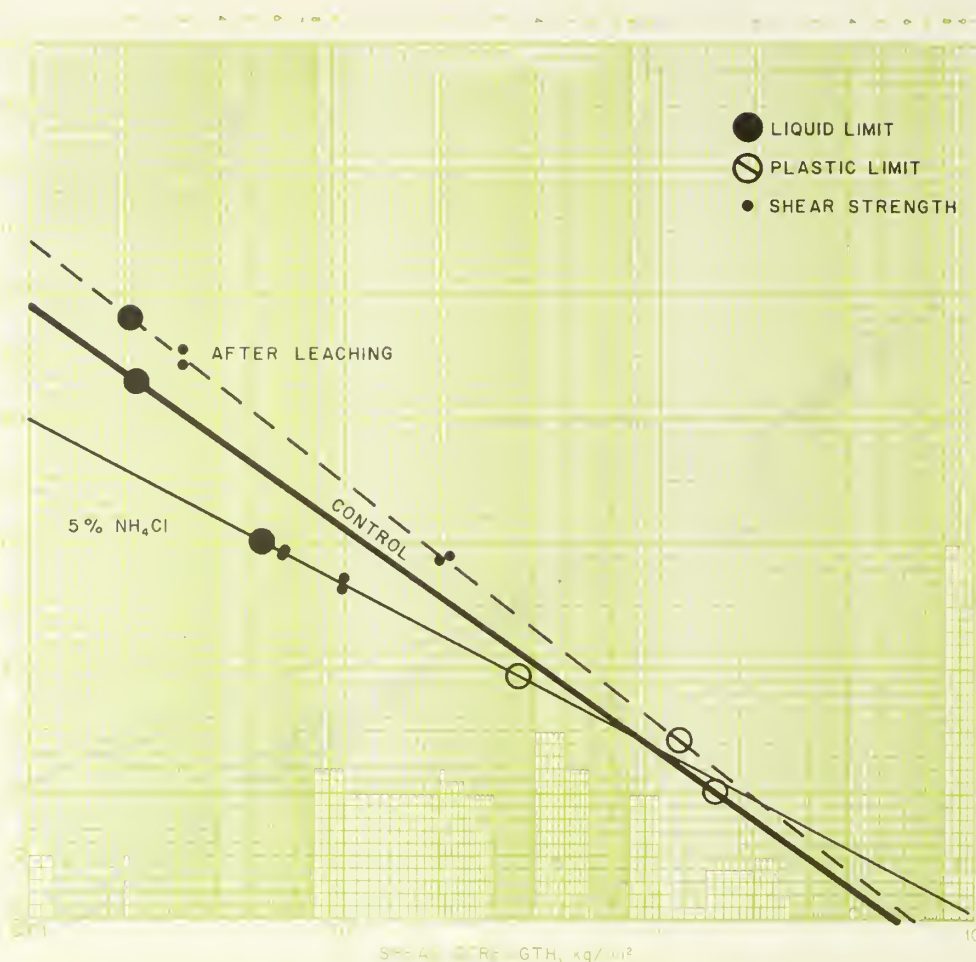


Figure 6. Shear curves for Diablo clay treated with 5% ammonium chloride

(1970), however, reported an increase in strength after six days contact. On the other hand, Woods and Yoder (1952) showed that soils treated with 0.5-1.5% calcium chloride usually have less penetration resistance (shear strength) and about 5% lower liquid limits than untreated soil.

Some of these differences can be explained by considering the moisture contents at which strength tests were run. For example, when 5% calcium chloride was added to a montmorillonitic landslide soil containing sodium and calcium sulfate, shear strength decreased at low water contents and increased at high water contents (Kerr, Stroud, and Drew, 1971). This is in accord with cohesive strength measurements made by Matsuo and Mise (1956) on a Ca-saturated soil after leaching. Their data imply that the LL would increase after a naturally Ca- and Mg-saturated soil was completely saturated with Ca and leached of excess salts. Without further tests, they recommended that a landslide be treated with Ca ions.

Another important factor in interpreting results is the clay mineralogy. For example, in the experiments reported by Mielenz and King (1955), the plasticity index (PI) of Na montmorillonite decreased from 660 to 114 when it was Ca-saturated. The PI of Na-beidellite decreased from 62 to 35 when it was Ca-saturated. Trivalent ions further decreased the PI of mont-

morillonite but not the PI of beidellite. The plasticity of kaolinite (Mielenz and King, 1955) and illite (mica) was generally unaffected by changes in ion saturation, though this is not the case for quick clays (Torrance, 1974). Shear strength also is increased upon addition of cations of a higher charge than the original saturation (Samuels, 1950). The increase in strength is much greater for highly charged clays, such as montmorillonite, than for clays such as kaolinite. Unfortunately, these data are not in agreement with the data of Aufmuth (1972), who found that calcium and magnesium chlorides reduced the unconfined compressive strength of montmorillonite but increased it for micaeous clays. Dowdy and Larson (1971) also found that the unconfined compressive strength of Ca-montmorillonite was greater than for Al-montmorillonite.

Quick clays (low in smectite) treated with 0.2% calcium or magnesium chloride had twice the strength they had when treated with that amount of sodium chloride (Talme, 1968). Calcium chloride was considered by Talme to be the best and cheapest chemical for stabilizing quick clays (for example, treating a ton of clay with 1 kg of CaCl<sub>2</sub> would cost only six cents).

Because our test soil is dominantly smectite, a decrease in the LL and a decrease in shear strength at high moisture contents was expected when the salt was added. This would be in agree-



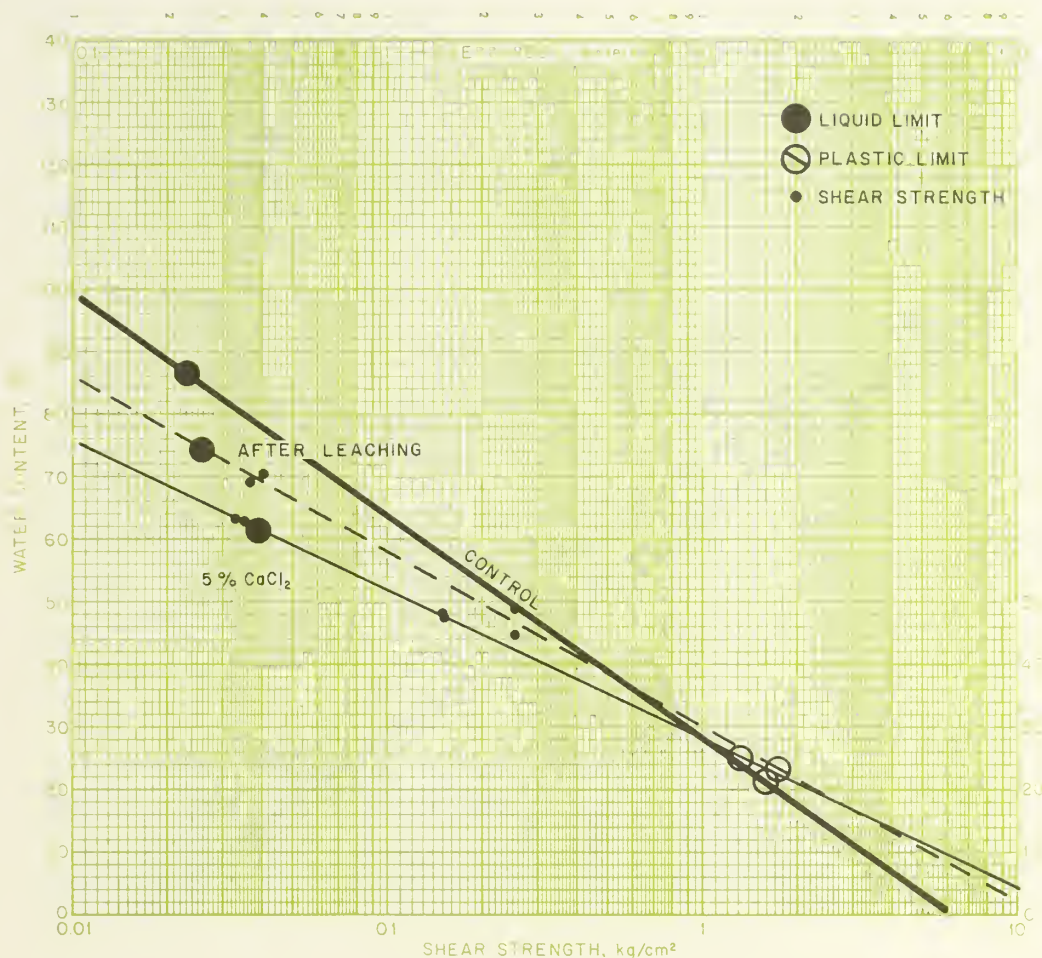


Figure 7. Shear curves for Diablo clay treated with 5% calcium chloride

ment with Ingles and Metcalf (1972), who say that calcium chloride tends to decrease compaction and increase permeability. Such changes occur primarily as a result of the high concentration of salt in the porewater. At low salt concentrations, the divalent Ca ion still causes expanding clays such as montmorillonite to contract and flocculate, but Na of equal ionic concentration causes them to expand and disperse.

**Treatment.** As expected, calcium chloride decreased the liquid limit and the shear strength of Diablo clay at high moisture contents (Figure 7). The presence of excess chloride salts caused flocculation and a probable increase in permeability, which is reflected in the decrease in LL.

**Leaching.** Calcium chloride would be easily leached away by rainfall. Experimental leaching of the calcium chloride-treated soil resulted in an increase of the LL from 61 to 74. The final LL was greater than for Al-treated soil after leaching (70) but less than for ammonium-treated soil after leaching (96).

## Ferric Chloride

**Literature.** Ferric chloride,  $\text{FeCl}_3$ , tripled the strength of a soil after six days contact (Kuhn, 1970). Quick clay treated with 0.2% ferric chloride had three times the strength of clay treated with the same amount of sodium chloride (Talme, 1968). The shear strength, LL, PL, and PI of quick clay increased after 1% ferric chloride was added (Moum, 1967). Ferric hydroxide (0.6%) also produced similar changes. However, ferric hydroxide was less effective than aluminum hydroxide for increasing the LL of quick clays (Loken, 1970). Fe-clay also had a lower PL than Al-clay. The increase in shear strength is much greater for quick clay when  $\text{Fe}^{3+}$  is added and then hydrolyzed than when ferric hydroxide is added.

Under certain unique environmental conditions, ferric iron may be involved in the interlayering of smectites to form non-expanding chlorites in soils (Jackson, 1963; Singleton and Harward, 1971). Poor drainage appears to reduce the amount of interlayering, presumably through reduction of ferric ion to the more soluble ferrous ion. In the laboratory, iron-saturated montmorillonite and vermiculite can be titrated with NaOH to form iron hydroxy interlayers (Carstea, Harward, and Knox, 1970a). These Fe-hydroxy interlayers decrease the swelling of Na-montmorillonite in NaCl solution (El Rayah and Rowell, 1973).

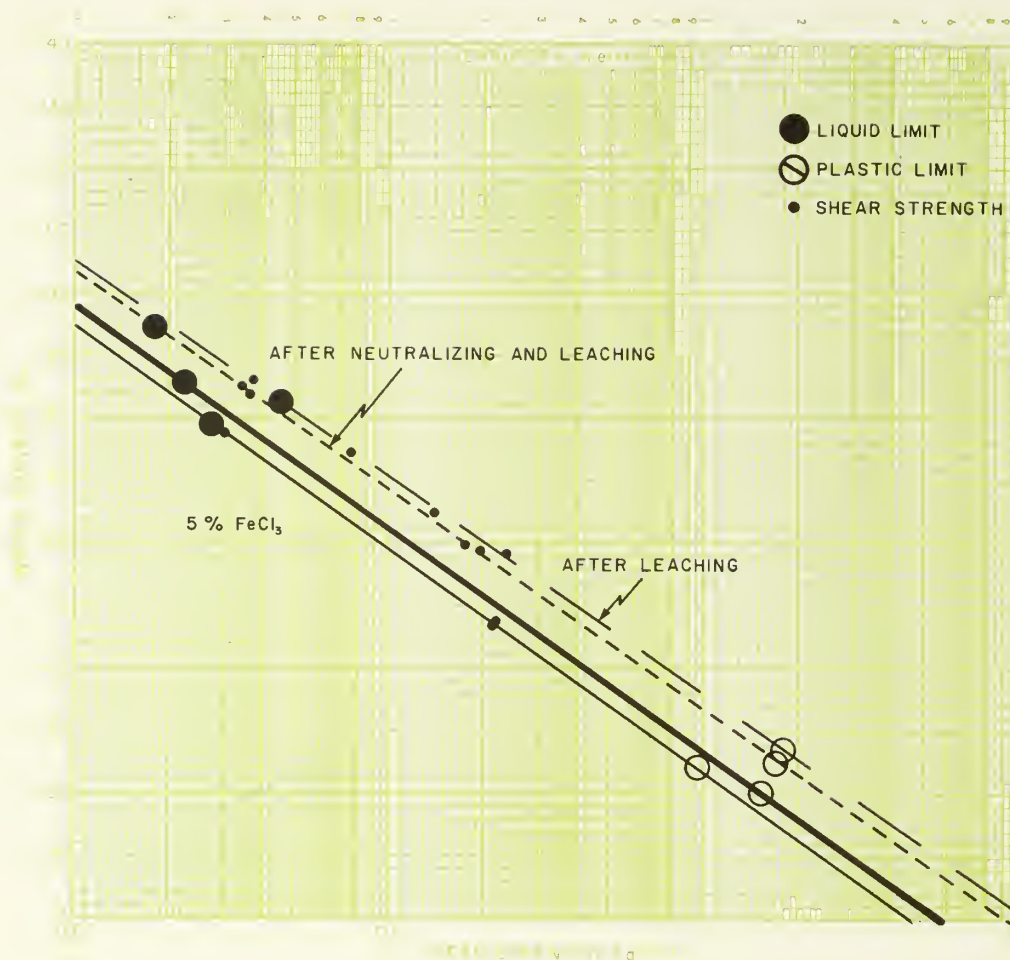


Figure 8. Shear curves for Diablo clay treated with 5% ferric chloride

**Treatment.** In our tests, ferric chloride produced slight decreases in shear strength at all moisture contents (Figure 8). This was the only chemical treatment to give any indication that a type G shear curve (Figure 1d) is possible. However, much more data are needed before these slight decreases in strength can be considered statistically significant. The LL decreased, and the PL increased, as was the case for treatments with other chloride salts. These changes produced a decrease in the plasticity index without the usual corresponding decline in the slope of the shear curve (compare Figure 3 with Figure 8).

**Leaching and neutralization.** Leaching excess salts from the ferric chloride-treated soil increased the LL from 79 to 83. When a ferric chloride-treated sample was neutralized with ammonium hydroxide, the LL increased to 95 and the shear strength increased at all moisture contents—a type H shear curve (compare with Figure 1d). Neutralization of ferric iron probably formed a gelatinous precipitate of ferric hydroxide that quickly changed to less hydrous forms of Fe, such as goethite,  $\text{FeOOH}$ . The increase in LL and high moisture strength probably is due to the hydrous oxides that others have shown to be cementing agents (Mehra and Jackson, 1960).

This neutralization process required 44 meq of ammonium

hydroxide to bring the pH of ferric chloride-treated soil from 1.8 (indicating an excess of ferric chloride in the pore solution) up to 6.0. This is equivalent to 1.42 hydroxyls per ferric ion. Obviously,  $\text{FeOOH}$  requires only one hydroxyl per ferric ion. A ratio greater than 1.0 indicates that iron still may be in the hydroxide form after neutralization. Because  $\text{Fe}(\text{OH})_3$  cannot exist in soils for long, the high-moisture shear strength would decline eventually. Weathering of soils treated with ferric chloride might be expected to result in a decrease in the slope of the shear curve while increasing the low-moisture strength. Therefore, the type H curve may be only a temporary phenomenon. In any case, ferric chloride may be expected to diminish, rather than improve, shear strength when it is first applied.

### Ferrous Chloride

**Literature.** Ferrous chloride,  $\text{FeCl}_2$ , furnishes highly soluble ferrous ions to the soil. This form of iron would remain in its reduced form only if it were added to a reduced soil, one that occurs beneath the water table. Because Diablo clay is a well-drained soil, it can be expected to have a high redox potential that will cause at least some of the ferrous iron to be oxidized to ferric iron. This must be considered when interpreting the work of others.



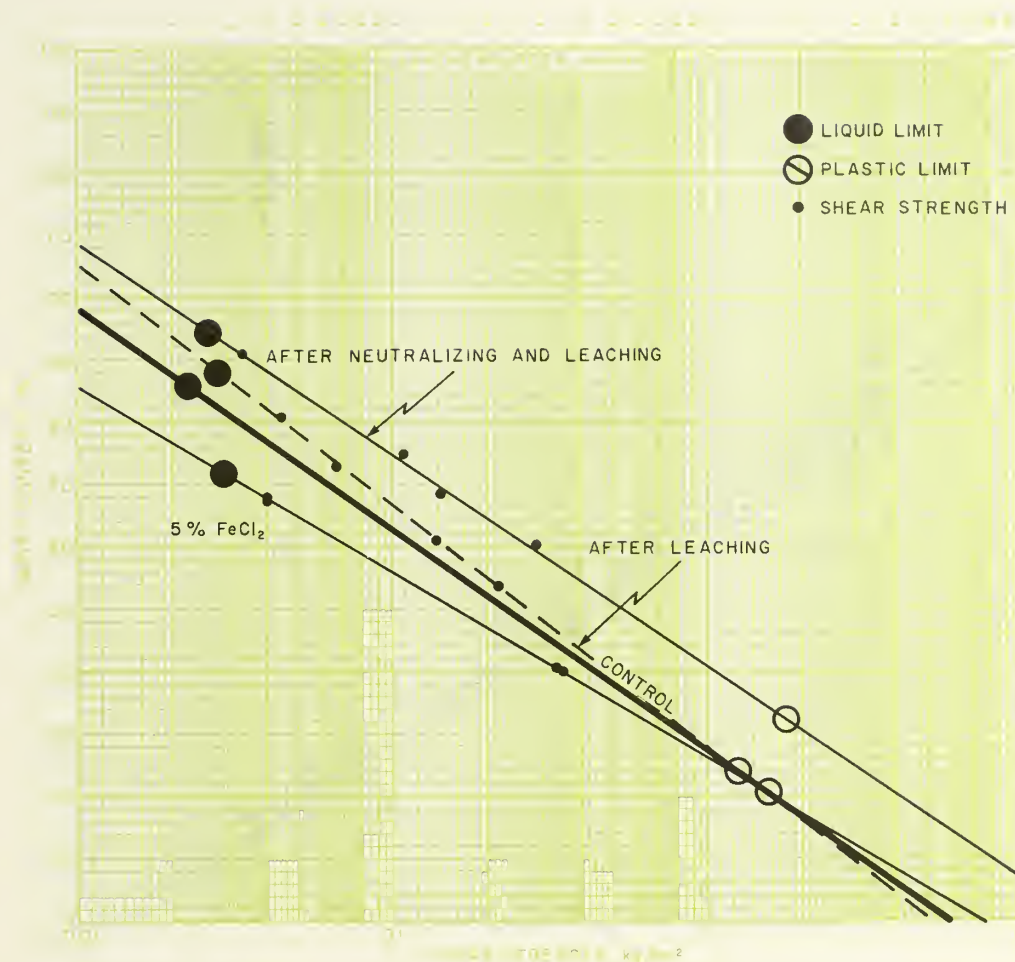


Figure 9. Shear curves for Diablo clay treated with 5% ferrous chloride

According to Moun, Sopp, and Loken (1968), ferrous chloride increases the shear strength of quick clays under conditions in which ferric chloride decreases the strength. Moun (1967) found that the shear strength, LL, PL, and PI of quick clay treated with 1.1% ferrous chloride increases as the clay is oxidized.

**Treatment.** We found that ferrous chloride treatment of Diablo clay reduced the LL from 86 to 72. Leaching the excess salt from the soil returned the LL and shear strength to slightly above normal (Figure 9). When the soil was neutralized and then leached, the shear strength increased at all moisture contents. The type H curve produced by this effect was more pronounced than the type H curve produced by neutralizing the ferric chloride soil (compare Figure 8). The LL increased to 95 and the PL increased to 33 as a result of neutralization. The difference between these two values gave a plasticity index of 62, a value slightly lower than the PI of the control (65). This was one of the few instances in which shear strength was increased at all moisture contents while soil expansion was reduced.

### Hydrochloric Acid

Acids might be useful for stabilizing landslides that do not contain limestone or other carbonate minerals that would neu-

tralize the acid. Occasionally, acids are used to solubilize other chemicals that would not otherwise diffuse through the soil.

**Literature.** The effect of acid on a neutral soil is complicated by the anion that accompanies the acid. Indeed, Ingles (1968) calls the low pH range, less than about pH 3, the range of anion stabilization. Anions, such as  $\text{PO}_4^{3-}$  or  $\text{F}^-$ , react with Al or Si to form insoluble compounds. Others,  $\text{Cl}^-$  for example, displace  $\text{OH}^-$  from the edges of minerals. Such true anion exchange is generally a very small proportion of the total ion exchange capacity of smectites such as those in Diablo clay (Borchardt, 1977a). Most of the initial reaction of hydrochloric acid,  $\text{HCl}$ , with smectite involves exchange of natural cations with hydronium ion,  $\text{H}_3\text{O}^+$ .

Reducing the pH of a soil below 3 tends to release trivalent cations, such as  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$ , from mineral structures. In particular, hydronium-saturated smectites tend to be unstable. The H-clays gradually change to Al- and Fe-clays when Al and Fe cations move from the octahedral sheet to the interlayer positions formerly occupied by hydronium molecules (Coleman and Harward, 1953). This conversion of H-clays to Al- or Fe-clays is highly temperature dependant (Mathers, Weed, and Coleman, 1955).

Al-saturated smectites tend to become interlayered with hydroxy aluminum polymers when the pH rises. The addition of

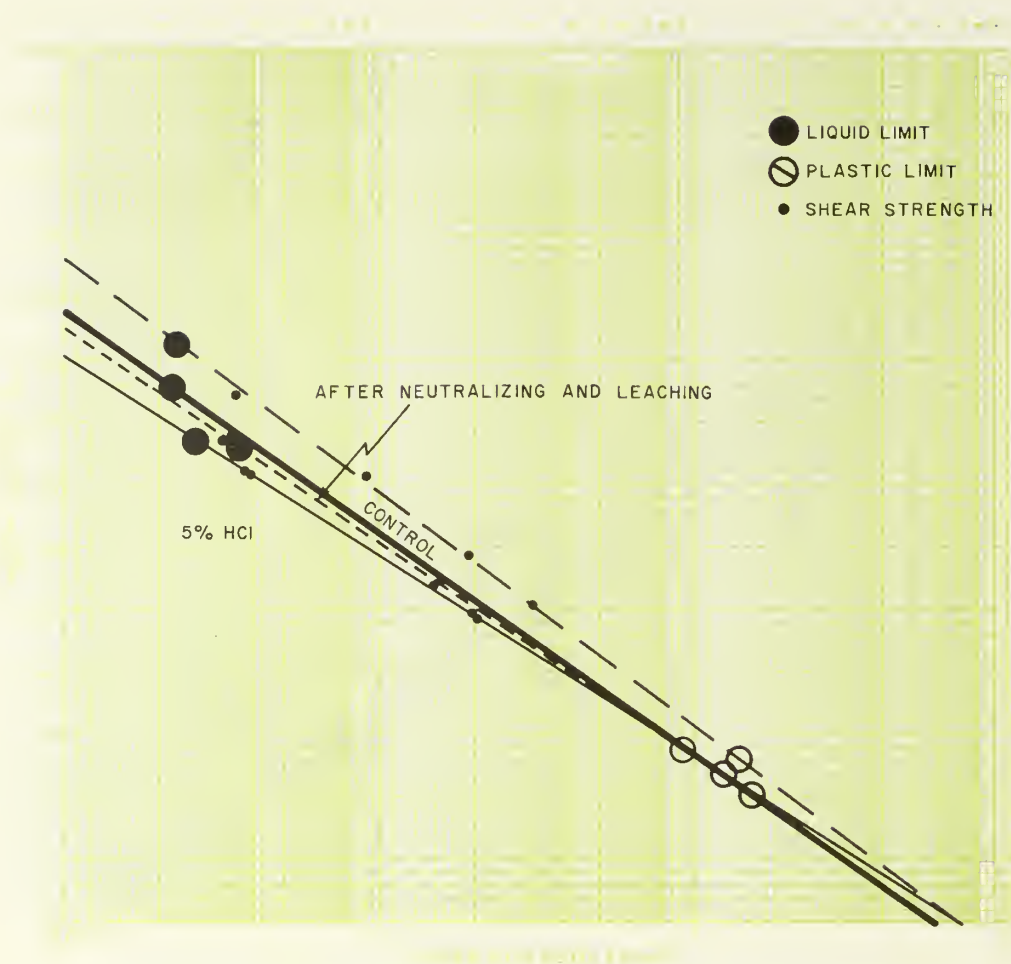


Figure 10. Shear curves for Diablo clay treated with 5% hydrochloric acid

an acid to a landslide will produce only a temporary reduction in pH. The pH will rise again due to the natural buffering capacity of the soil. Therefore, hydroxylation of liberated Fe and Al can be expected to convert some expanding clays to chlorite-like minerals.

Truly H-saturated montmorillonite has a much higher liquid limit than clay saturated with Ca, Mg, Fe, or Al (Mielenz and King, 1955, p. 220). In the experiments by Mielenz and King, for example, H-montmorillonite had an LL of 380 while Ca-montmorillonite had an LL of 157. References to soils stabilized with HCl are few, but Rosenqvist (1955) found that it decreased the shear strength of quick clays.

**Treatment.** We found that five percent amounts of HCl slightly reduced the shear strength of Diablo clay (Figure 10). There was a decrease in LL from 86 to 77 and an increase in PL from 21 to 24. Neutralization was achieved with ammonium hydroxide, and the resulting ammonium chloride was leached away with distilled water. This caused the shear strength to return to normal, while the LL remained unchanged. The soil at this point does not contain significant quantities of  $\text{NH}_4^+$  or  $\text{H}_3\text{O}^+$  on the exchange. Both ammonium (Figure 6) and hydronium (Mielenz and King, 1955, p. 220) would have produced an LL greater than the control value. The initially H-saturated clay obviously has been converted to Al- or Fe-clay. Even though some polymerization and interlayer formation may have occurred, the shear strength was not significantly affected.

**Neutralizing and Leaching.** Neutralizing and leaching increased the PL from 24 to 28. Such an increase in PL appears characteristic of other acidic treatments as well.

### Potassium Chloride

**Literature.** Certain clay minerals have a high affinity for certain cations. Vermiculite, for example, collapses readily when monovalent or divalent cations are replaced with K (Alexiades and Jackson, 1966). Berkland (1969) has suggested the addition of potassium salts as a means of stabilizing slopes having large amounts of vermiculite. In regard to clay mineralogy, Zaruba and Mencl (1969, p. 116) state that "K-ions cause a closer arrangement of elementary layers in montmorillonitic clays. This results in the squeezing out of some quantity of free water and thus, in decreased strength after remoulding. This is of practical importance near the surface of slopes, as K-ions loosened by weathering increase the strength of illitic clays but can have an unpropitious effect on montmorillonitic clays in unstable areas." They also mention that K removal from glauconite has contributed to slope failure.

In accord with this, Aufmuth (1972) found that KCl reduced the unconfined compressive strength of montmorillonite and kaolinite but increased it for micaceous clay. KCl has twice the efficiency of NaCl in improving the remoulded shear strength of quick clays (Rosenqvist, 1955). Similarly, the shear strength of



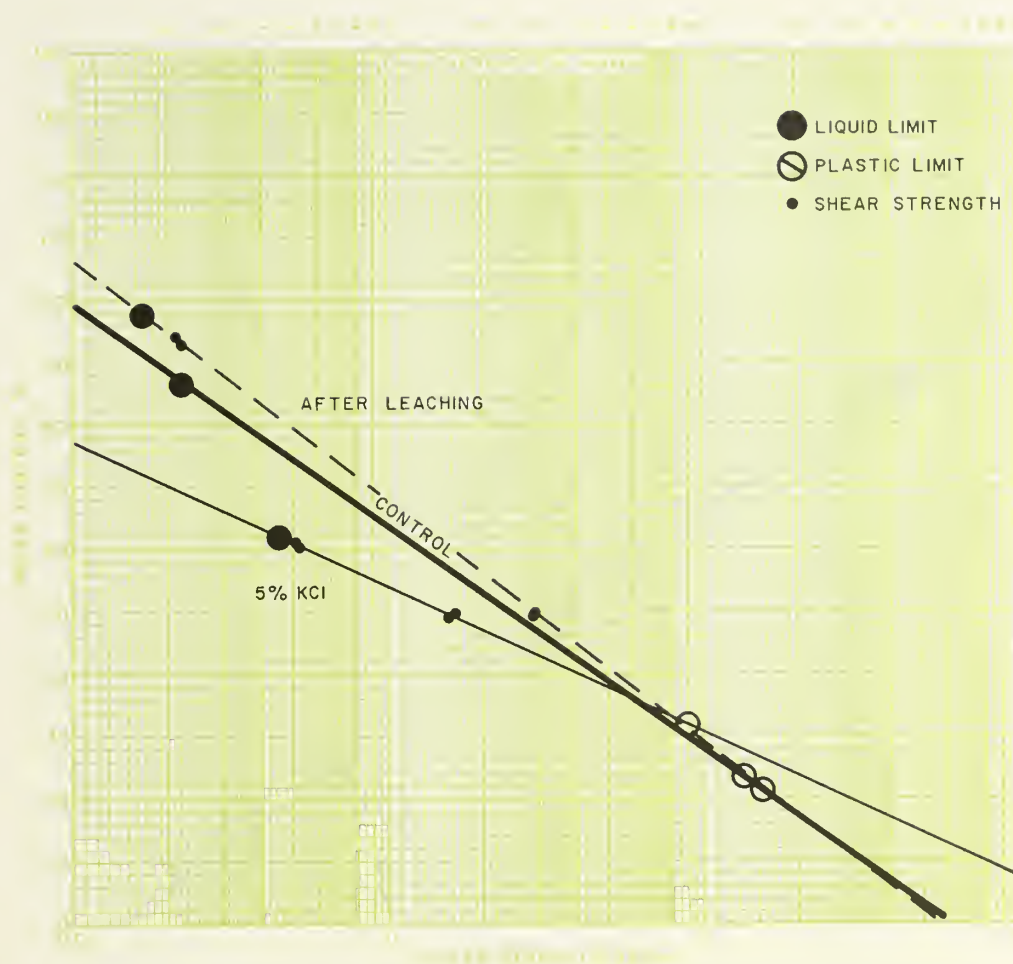


Figure 11. Shear curves for Diablo clay treated with 5% potassium chloride

quick clay increased from 1.4 to 4.6 t/m<sup>2</sup> with additions of 5% KCl (Moum, Sopp, and Loken, 1968, p. 3). The strength decreased to 3.8 t/m<sup>2</sup> when 22% KCl was added. KCl diffused 30 cm in 85 days. The other chemicals—ferrous chloride, ferric chloride, aluminum chloride, calcium hydroxide, and sulfuric acid—take “part in complicated chemical reactions with the clay system and make it very difficult to calculate any meaningful diffusion coefficients” (Moum, Sopp, and Loken, 1968). Overall, KCl is considered better than calcium hydroxide for stabilizing landslides in quick clay.

In other work, KCl in combination with electro osmosis reduced soil expansion by factors between 2 and 8 (O'Bannon, 1972). The effectiveness increased with decreases in water content and increases in montmorillonite content. Winterkorn and Moorman (1941) reported an increase in the angle of internal friction when clay was saturated with K.

**Treatment.** We found that KCl decreased the high-moisture strength and increased the low moisture strength of Diablo clay (Figure 11). The LL decreased from 86 to 61 and the PL increased from 21 to 31. Expansivity decreased by a half as the PI decreased from 65 to 30. These results at first appear to agree with those in the literature for smectitic soils at moisture contents above the plastic limit.

**Leaching.** However, the temporary nature of the KCl treatment was obvious after the leaching step (Figure 11). The effect on shear strength that Zaruba and Mencl (1969) attributed to K-ions probably resulted instead from the presence of excess salt in the pore solution. By removing excess KCl, the PL and the shear strength returned to values slightly above normal. The LL increased from 61 to 97 as a result of leaching. The LL of K-saturated, Wyoming montmorillonite was 218, whereas the LL of Ca-saturated montmorillonite was only 157 (Mielenz and King, 1955, p. 220). Therefore, the increase in LL to a value 11 points above the control value could have resulted only from exchange of K<sup>+</sup> for naturally occurring Mg<sup>2+</sup> or Ca<sup>2+</sup>. Also, KCl-treated Diablo clay ultimately would be more expansive (PI=73) than untreated soil (PI=65).

### Sodium Chloride

**Literature.** The shear strength of Na-montmorillonite is greater than the shear strength of Ca-montmorillonite at a constant void ratio (Warkentin and Yong, 1962). Likewise, the liquid limit decreases as the salt concentration of the pore-water increases. The unconfined compressive strength of Na-montmorillonite was greater than for Ca-montmorillonite at constant water content (Dowdy and Larson, 1971). Yong and Warkentin

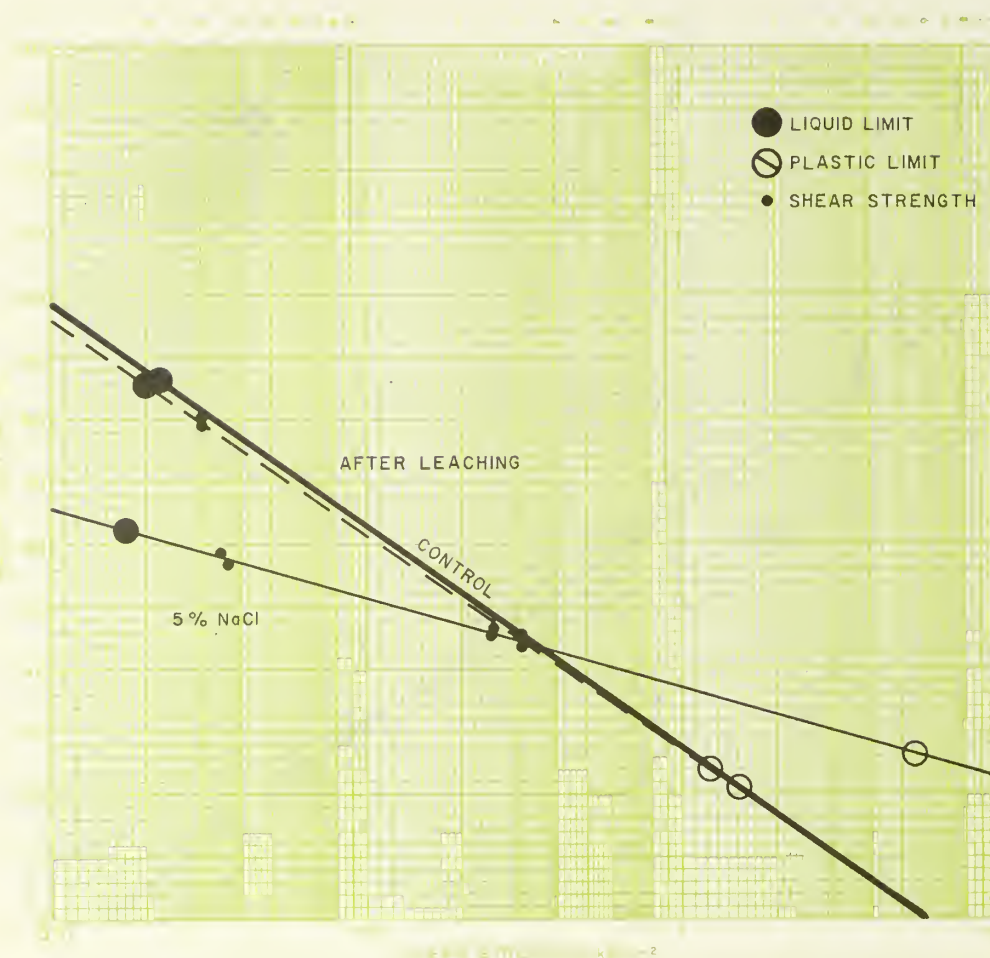


Figure 12. Shear curves for Diablo clay treated with 5% sodium chloride

(1966, p. 99) mention that Na increases the LL of montmorillonite but decreases the LL of low swelling clays like kaolinite. However, the addition of NaCl (without subsequent leaching) decreased the unconfined compressive strength of both montmorillonite and kaolinite (Aufmuth, 1972). The strength of partially Na-saturated clays was demonstrated by Mitchell and Eden (1972) and Sangrey and Paul (1971), who observed fewer landslides when the Na/Ca ratio of the pore water was high than when it was low. Thus, the cohesiveness of Na-saturated smectite is greater than the cohesiveness of Ca-saturated clay. Cohesion, however, is not the only factor affecting landslides. It must be considered in relation to moisture content, permeability, and other factors.

**Sodium and permeability.** For chemical treatments with Na, an important factor involves soil permeability. The permeability of a Ca-montmorillonite membrane is 14 times that of a Na-montmorillonite membrane (Shainberg and Caiserman, 1971). This difference in permeability was illustrated in a classical study by Lee (1941). A lagoon on Treasure Island in San Francisco Bay had been lined with clay to prevent seepage of fresh water. Seepage however, was excessive—the water level declined at the rate of 23 mm/day. When sea water was added and leached by fresh water, the seepage rate decreased to only 3 mm/day. The resulting Na-saturated clay was very cohesive and nearly impervious.

Interestingly, permeability and swelling are unaffected by Na unless exchangeable Na on montmorillonite is greater than 15% (Shainberg, Bresler and Klausner, 1971). Due to the low affinity of montmorillonite for Na (Carroll, 1959), massive amounts (greater than 10g/100 g soil) of NaCl would be necessary to displace that much Mg or Ca from Diablo clay. When NaCl is added in only 5% amounts, a temporary increase in soil permeability due to high salinity in the porewater can be expected (Quirk and Schofield, 1955), but after drainage and leaching, the soil permeability and soil swelling would return to normal.

**Quick clay.** Quick clays present an entirely different and generally contrasting picture. They also deserve mention because there is considerable literature on the effect of NaCl on quick clay. This is because most quick clays are believed to have been flocculated from sea water (Aune, 1966). Natural leaching by rainfall removes NaCl and other sea water salts from soil pores without collapsing the fragile structure. The soil pores remain filled with water—so much so that natural moisture contents of quick clays are always greater than their liquid limits. For this reason, quick clays are susceptible to sudden liquefaction under sufficient mechanical disturbance.

Basically, the addition of NaCl increases the strength of quick clays, whereas it normally decreases the strength of smectitic clays. For example, 0.14 to 1.15% NaCl increased the LL, PL,

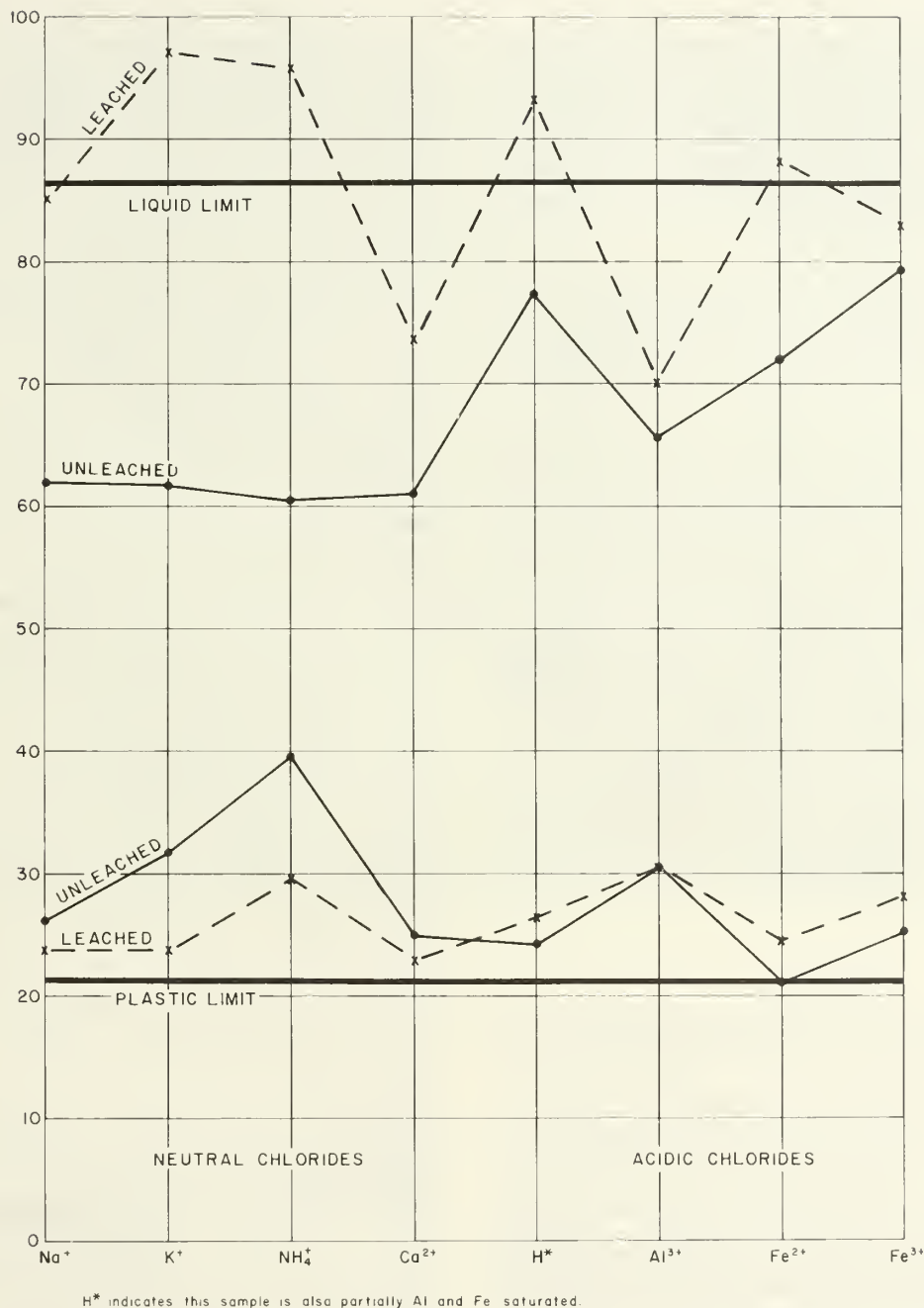


Figure 13. Effect of 5% quantities of chloride salts on the Atterberg limits of Diablo clay before and after leaching.

PI, and shear strength of quick clays (Loken, 1970). Increases also occurred for other chloride salts of potassium, magnesium, ferrous iron, ferric iron, and aluminum. Further gains were noted after 26 days of contact.

For another quick clay, 1% NaCl increased the LL from 35 to 60 (Rosenqvist, 1955, p. 75). The LL remained constant at concentrations up to 7% NaCl, after which the LL began to decline. A quick clay treated with 3.9% NaCl had an LL of 43, but after leaching the LL decreased to 27. Drying also produced a decrease in LL in saline quick clays.

The PL is less easily influenced by salinity. Rosenqvist (1955) found that the PL of quick clays increased slowly with each increase in NaCl. The PL decreased only slightly after leaching. Overall, NaCl produced a general increase in the plasticity index

in quick clays. Likewise, the addition of 3.5% NaCl increased the PI from 12 to 29 for one quick clay and from 20 to 39 for another (Rosenqvist, 1955, p. 43). The PI of a different quick clay increased with increasing salt concentration up to 1 or 1.5% but was nearly constant for higher concentrations (Bjerrum, 1954).

Torrance (1974, 1975) found similar results for Canadian quick clays. The dominant minerals in quick clays are quartz, feldspar, silicates such as mica (illite), and chlorite. Liebling and Kerr (1965) studied the effect of NaCl on two of these minerals. The shear strength and permeability of quartz (less than 44  $\mu\text{m}$ ) was unchanged by NaCl, but the strength and permeability of illite decreased. "Illite" actually consists of mica pseudomorphs that contain expanded layers of vermiculite and smectite (Bor-



hardt, Jackson, and Hole, 1966). Illite, therefore, behaves more like smectite than like quick clays, whose strength improves in the presence of salt. Indeed, the addition of as little as 4% montmorillonite increased shear strength and decreased the sensitivity of quick clay (Torrance, 1974). The natural smectite contents apparently are too low to counteract the decrease in strength that occurs when NaCl is leached from the low-swelling minerals that dominate quick clays.

**Treatment.** Of all chemical treatments of Diablo clay, NaCl produced the largest decrease in the slope of the shear curve (Figure 12). Shear strength increased at low moisture contents but decreased at high moisture contents. The LL decreased to 62, a value similar to that of the other neutral chlorides (Figures 6, 7, 11, and 12).

**Leaching.** These changes in LL and shear strength relate strictly to the high ionic strength of the porewater. As expected for expanding clays, the LL and shear strength returned to normal after the excess salt was removed by leaching. The physical properties of Diablo clay were not permanently affected by 5% NaCl. There are at least two important reasons for this. First, the cation exchange capacity (CEC) of Diablo clay was very high—57.7 meq/100 g soil. Second, the amount of NaCl added to the soil was relatively low (86.5 meq/100 g soil, Table 2). Apparently, this amount of Na replaced less than 15% of the natural  $Mg^{2+}$  or  $Ca^{2+}$ . As previously mentioned, most clays must be at least 15% Na saturated before their physical properties are affected by the  $Na^+$  cation. If the CEC of the clay had been less or the amount of salt had been greater, LL and shear strength might have increased after leaching. At least 10 g NaCl/100 g of Diablo soil would be needed to achieve a permanent increase in the LL and shear strength.

## Conclusions

In general, the chloride salts have one major disadvantage for stabilizing smectite-bearing landslides—they first lower the shear strength before increasing it. For non-expansive clays, the results could be the opposite. Increasing the ionic strength of a porewater associated with expansive clays causes the liquid limit and high-moisture strength to decrease. In these experiments, each of the neutral chlorides decreased the LL from 86 to 61 (Figure 13). The acidic chlorides were of similar weight but higher ionic strength and probably were involved in complex reactions forming polymers that block the collapse of smectites. For whatever reasons, the unleached acidic chlorides did not decrease the LL as much as did the neutral chlorides (Figure 13).

Both the liquid limit and shear strength increase when excess salt is leached from the soil by rainfall or artificial means and the effect of cation exchange begins to appear. How much cation exchange occurs and how much the physical properties of the clay are altered from the natural condition depends upon several important factors: (1) the type of cations on the exchange of the clay; (2) the type of cation being added; (3) the type of minerals responsible for the cation exchange capacity (CEC); (4) the CEC of the soil; and (5) the ionic strength of the porewater during cation exchange. Increases in shear strength produced by cation exchange are likely to correspond to increases in the liquid limit. For montmorillonite saturated with various cations, the LL decreases in the following order:  $Na^+ > H^+ > K^+ > Ca^{2+} > Al^{3+} > Fe^{3+}$  (Mielenz and King, 1955, p. 220). This means that Na exchange would increase the LL of a K-montmorillonite, but Ca would decrease it. It is possible for a soil montmorillonite to have each of these cations on the exchange. Most neutral soils, such as Diablo clay, are primarily Ca and Mg saturated. Therefore cations such as  $K^+$  can be expected to increase the LL of montmorillonitic Diablo clay (Figure 13). On the other hand,  $Al^{3+}$  or  $Fe^{3+}$  would tend to decrease the LL. The LL of beidellite, an aluminous smectite, apparently has a different response to changes in cation saturation (Mielenz and King, 1955, p. 220). For non-swelling clays like kaolinite, the Al-saturated version may have a higher LL than the K-saturated one. The alteration of shear strength by cation exchange is obviously a function of the soil mineralogy.

The concept of *symmetry* (Carroll, 1959) is necessary for understanding the relationship between soil CEC and ionic strength of soil porewater. In the study of cation exchange, one symmetry is considered the amount of salt equal to the cation exchange capacity. Carroll (1959) showed that one symmetry of NaCl replaced 11.4% of the Ca from Ca-montmorillonite whereas one symmetry of KCl replaced 25.2%. These values may vary depending on the type of clay minerals present, but K is always selectively adsorbed over Na. For montmorillonite, the replacing power of K is twice as great as Na. In addition, the replacement would have to be greater than about 15% for Na to have any effect on the physical properties of a soil. The CEC of Diablo clay is so high (57.7 meq/100 g) that 5% NaCl (1.48 symmetry, Table 2) was not enough to affect the LL after leaching (Figure 13). If more than 15% of the natural Ca or Mg had been replaced, the LL would have increased as it did for 1.16 symmetry of KCl (Table 2 and Figure 13).

The "replacing power" of small, highly-charged cations such as  $Al^{3+}$  is much greater than that of large, monovalent cations such as  $K^+$ . This is best illustrated by the sample treated with aluminum chloride (Figure 13). After leaching the excess salts away, the LL of this sample was reduced to 70. Thus, of the eight chlorides studied, aluminum chloride produced the greatest

Table 2. Ionic strength of porewater in Diablo clay at the liquid limit. Each soil sample contains 5 g of the chloride salt per 100 g of soil.

CDMG Lab. No.	Salt	Quantity of salt, meq	Porewater volume per 100 g of soil at the liquid limit, ml	Normality of porewater	No. of symmetries <sup>1</sup>
144/74	NaCl	85.6	62.0	1.38	1.48
145/75	KCl	67.1	61.7	1.09	1.16
162/74	$NH_4Cl$	93.5	60.5	1.55	1.62
41/74	$CaCl_2$	90.1	61.1	1.47	1.56
51/74	HCl	137.1	77.6	1.77	2.38
33/74	$AlCl_3$	112.5	65.8	1.71	1.95
67/75	$FeCl_2$	78.9	72.0	1.10	1.37
47/74	$FeCl_3$	92.5	79.5	1.16	1.60

<sup>1</sup> See Carroll (1959). Symmetry = meq of salt / CEC of soil (57.7 meq)



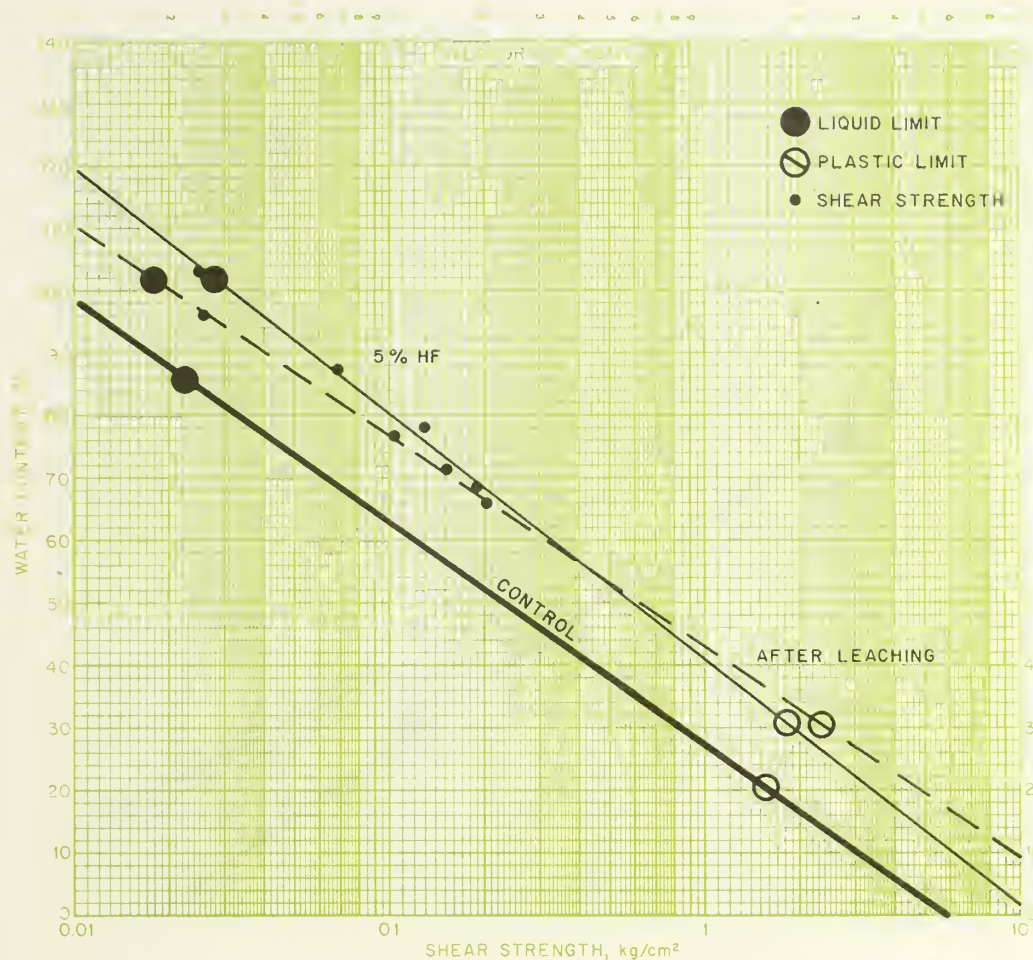


Figure 14. Shear curves for Diablo clay treated with 5% HF after one week of contact

change in LL, which presumably indicates that Al produced the greatest amount of cation exchange.

## FLUORIDES

We saw in the last section that chloride salts tend to decrease the shear strength of Diablo clay until the chloride salts are leached or neutralized. The increase in the ionic strength of the soil porewater causes smectites to collapse, releasing water. The collapse of smectites decreases the LL and shear strength at high moisture contents. Cation exchange occurs, but its strength-improving effects are not revealed until excess salt is leached away. We saw also that acidic salts like aluminum chloride seem to improve strength through interlayer formation in smectites, but that this improvement is not realized until the lengthy process of soil neutralization is completed.

The two fluorides treated in this section, hydrofluoric acid and potassium fluoride, are, like the chlorides, very soluble and thus amenable to liquid application to landslides. Unlike most chlorides, these fluorides form certain reaction products that are highly insoluble. These compounds may act as cementing agents that bind clay particles together and thus strengthen the soil.

## Hydrofluoric Acid

**Literature.** Hydrofluoric acid, HF, is an extremely effective stabilizer for all but the low-silica materials such as gibbsitic soil and bauxite (Ingles, 1970). It reacts with silicates to form coatings of insoluble fluo-silicates that are stronger than unreacted clay. Unlike the alkaline treatments, HF treatment destroys some of the high cation exchange capacity (CEC) of montmorillonite. This would be expected to result in a decrease in the high-moisture strength normally provided by untreated smectites.

Unfortunately, the handling problems of HF are acute, and the cost is extremely high. Even so, it was important to test HF in order to study the effect of the formation of insoluble compounds on shear strength and Atterberg limits. Although HF is known to decrease the LL of quick clay (Torrance, 1975), there were no previous studies of its effects on smectite.

Sometimes additives can improve the effectiveness of chemical action. HF appears amenable to this approach. For example, trichloroacetic acid was successfully used with HF for making sandstones more permeable (Bond and Lorenz, 1953). Five moles of HF and 2.5 moles of halogenated acetic acid per liter were used to get an oil well flowing again. Acid was left in the formation for 1-2 hours and then flushed out to prevent precipi-

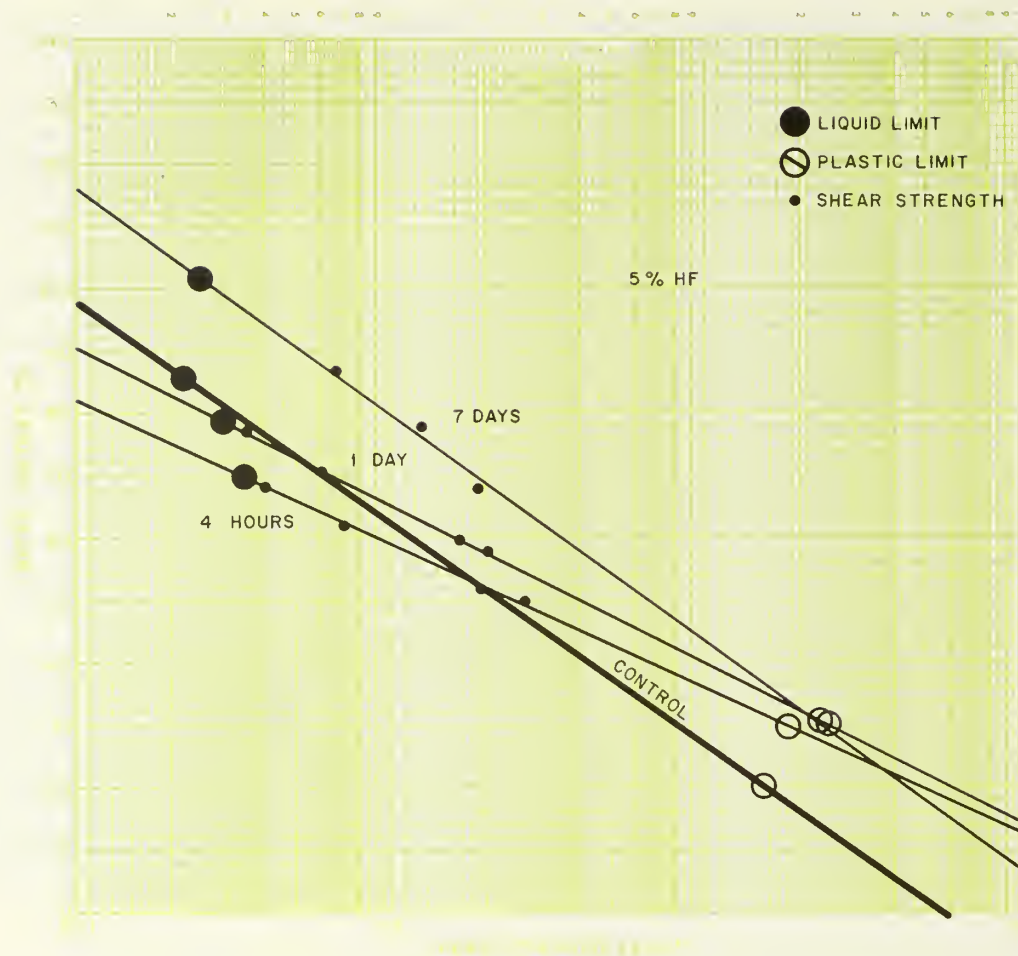


Figure 15. Shear curves for Diablo clay treated with 5% HF after four hours, one day, and seven days of contact

tation and plugging. With trichloroacetic acid, 13.5% sand was dissolved by HF. Without trichloroacetic acid, only 7.9% of the sand was dissolved by HF. The reactivity of 13.5 *M* HF with 4.2 *M* trichloroacetic acid is equivalent to that of 19 *M* HF, which is much more dangerous to handle.

HF, in turn, can be used as an additive to improve phosphoric acid stabilization of soils (Lyons, McEwan, and Siebenthal, 1962). We tested phosphoric acid as an additive to improve HF stabilization of landslides. Theoretically, HF would react with Si, and phosphoric acid would react with Al and Fe to form insoluble cementing agents in a wide range of soil types.

**Treatment.** HF appears to be one of the few chemicals to increase the shear strength of smectitic clay at all moisture contents (Figure 14). Unlike results with chlorides, treatment with HF increased both the LL and the PL. The fluosilicate cements presumably formed during the first week of contact were extremely insoluble and largely unaffected by leaching.

**Time.** The development of high-moisture strength corresponded with increases in the liquid limit (LL) over time (Figure 15). The plastic limit (PL) increased from 21 to 31 within

the first 4 hours of contact while the LL decreased from 86 to 70. This initial reaction appears to be similar to that of the soluble salts like NaCl. However, in the case of HF, the LL gradually increased to 102 after 7 days contact (Figure 15). Corresponding increases in high-moisture strength also occurred. One week appears to be sufficient time to form the fluosilicate cements. Tests at 12 and 30 days did not show any further changes in strength (Figure 16). The measured LL at 30 days was 115, showing that the LL apparently can increase without an increase in shear strength.

**Concentration.** The effect of concentration was tested by adding increasing amounts of HF and observing the results after 12 days (Figure 17). Even 1% HF doubled the shear strength at 40% moisture. Three percent HF tripled the strength while 5% HF quadrupled it at 40% moisture. Amounts greater than 5% produced no further changes in shear strength (Figure 18). This is particularly significant during the early stages of a landslide treatment procedure when quantities of a chemical are likely to be very high in certain parts of the landslide. Other chemicals react more slowly and less completely. The detrimental effects of high ionic strength are exaggerated under such circumstances, and actual decreases in shear strength can occur at high concentrations of a chemical. Fortunately, the optimum quantity of HF



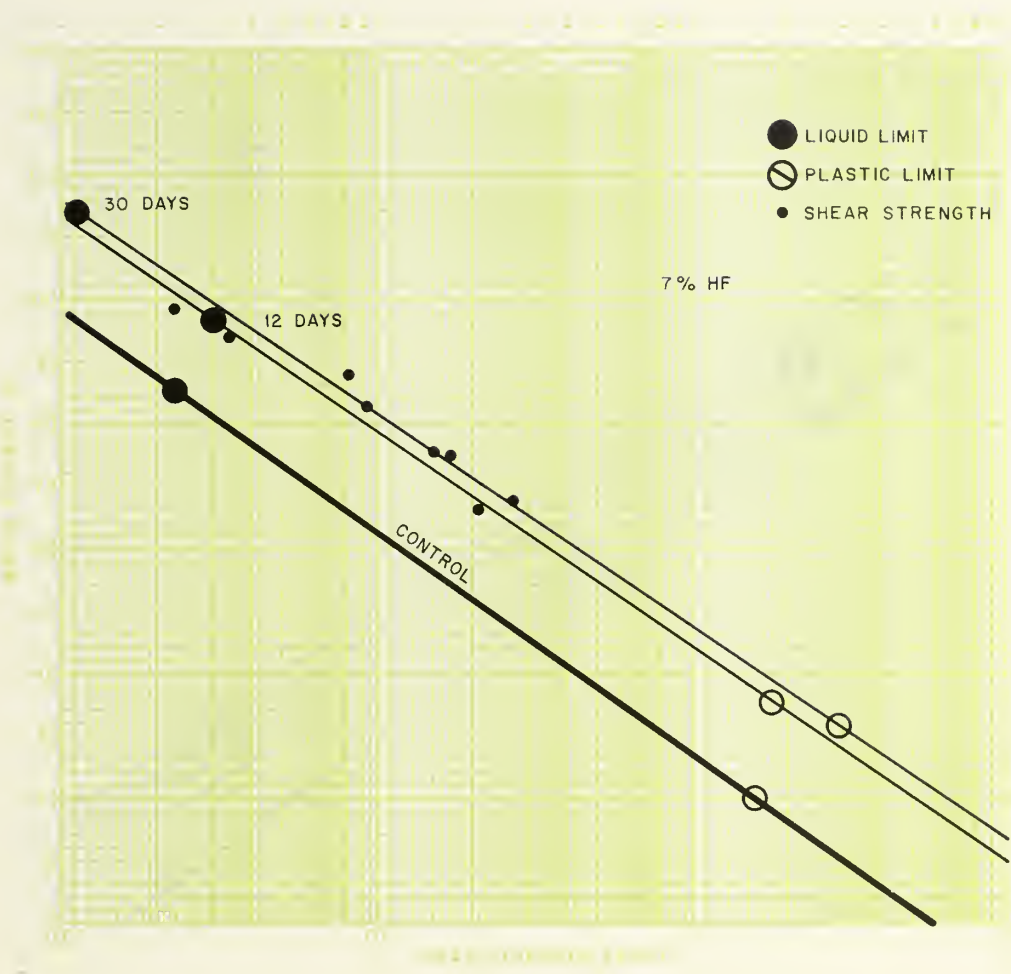


Figure 16. Shear curves for Diablo clay treated with 7% HF after 12 and 30 days of contact

for treating Diablo clay, 5%, is within the realm of practical application. It also happens to be the proportion chosen to test the other chemicals in this study.

HF appears to be a most promising chemical for landslide stabilization. This will have to be balanced against the extreme hazard of working with HF as well as its high cost (about \$5/kg). Small amounts of additives such as trichloroacetic acid (about \$20/kg) may improve the effectiveness while reducing cost. Another way to reduce costs would be to substitute large amounts of a similarly effective though cheaper chemical such as phosphoric acid (about \$1.50/kg).

*Effect of phosphoric acid on HF treatment.* Phosphoric acid was evaluated as an additive for the HF treatment (Figure 19). A mixture of 2.5% HF and 2.5% phosphoric acid increased shear strength at all moisture contents. However, except for a slight depression in the LL, there was no significant improvement over a treatment with 3% HF alone. The insoluble cementing agents produced by phosphoric acid provided no

improvement that was not otherwise provided equally well by HF. Phosphoric acid is thus not recommended as an additive for landslide stabilization under these conditions.

*Possible reactions between hydrofluoric acid and soil.* The H-type curve (increases in shear strength at all moisture contents) produced by HF appears ideal for landslide stabilization. A plausible explanation for the effectiveness of the HF treatment at all moisture contents is that the HF favorably affects many soil particles or interlayer surfaces. Apparently, HF is able to react with Si on the internal surfaces of smectite as well as on the external surfaces of soil particles. This reaction takes place within 7 days (Figures 15 and 16) and requires no more than 5 g HF/100 g of Diablo clay (Figures 17 and 18). The formation of fluosilicate coatings (Ingles, 1970) must be complete at this point because more time and further additions of HF do not produce further changes in physical properties. The mechanism responsible for these physical changes will become clearer as the relationships between HF utilization, CEC, exchangeable cations, and reaction rates are considered.



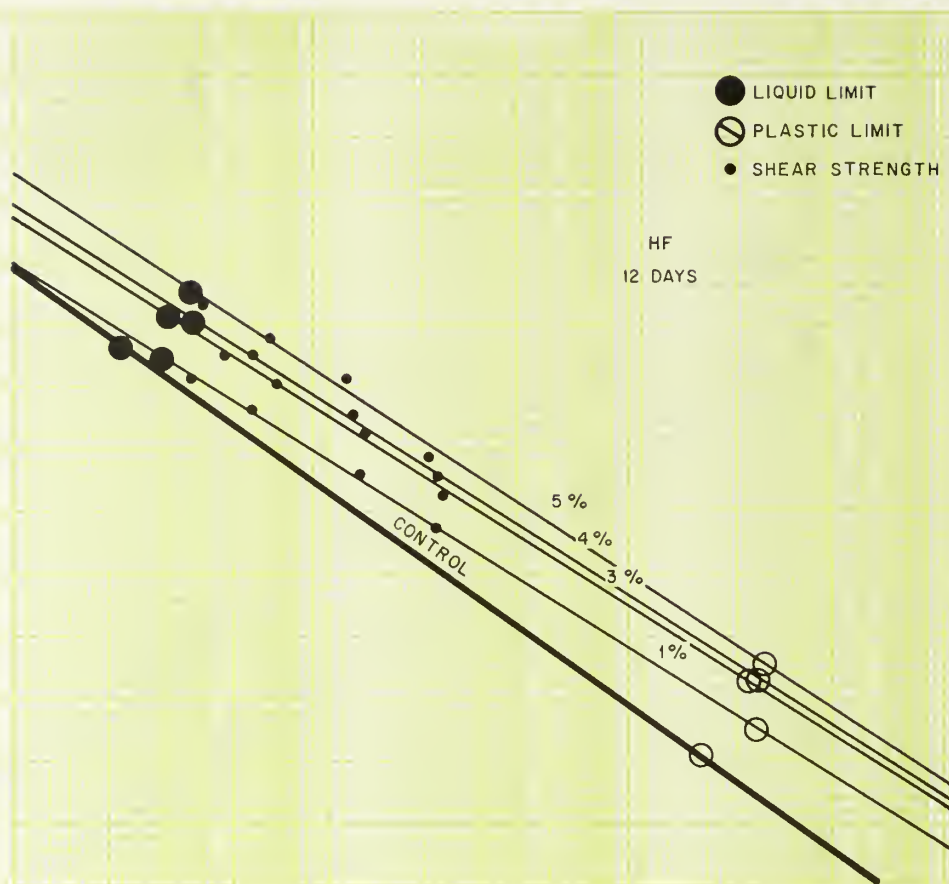
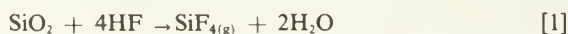
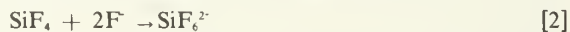


Figure 17. Shear curves for Diablo clay showing increases in strength as HF concentration increases from 1 to 5%

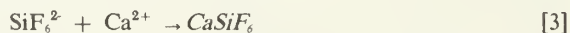
The most probable reaction between HF and silicates involves the formation of silicon tetrafluoride gas (Laubengayer, 1957, p. 425):



Fluorine is the only halogen that is small enough to accommodate two additional atoms in coordination with Si:



The result is a stable complex anion that forms insoluble fluosilicates (Table 3) with other cations:



Clearly, the available cations will determine which fluosilicates will form. The most insoluble fluosilicates that might form from major elements that occur in soils are: aluminum fluosilicate, calcium fluosilicate, potassium fluosilicate, and sodium fluosili-

cate (Table 3). Magnesium and iron fluosilicate would be too soluble to resist the leaching step included in these experiments (Figure 14). It is doubtful if the insoluble Al-fluosilicate, topaz, would form under these conditions. Therefore, the most likely fluosilicates to form are those of Ca, Na, and K.

Table 3. Solubilities of the fluosilicates that form from major elements in soils.

Fluosilicate	Solubility at 25°C (g/100 ml H <sub>2</sub> O) *
2AlFO·SiO <sub>2</sub> (topaz)	insoluble
CaSiF <sub>6</sub>	slightly soluble
K <sub>2</sub> SiF <sub>6</sub> (hieratite)	0.20
Na <sub>2</sub> SiF <sub>6</sub>	0.30
MgSiF <sub>6</sub>	65.0
FeSiF <sub>6</sub> ·6H <sub>2</sub> O (exist?)	128.2
Fe <sub>2</sub> (SiF <sub>6</sub> ) <sub>3</sub>	soluble

\* From Weast and others (1965).

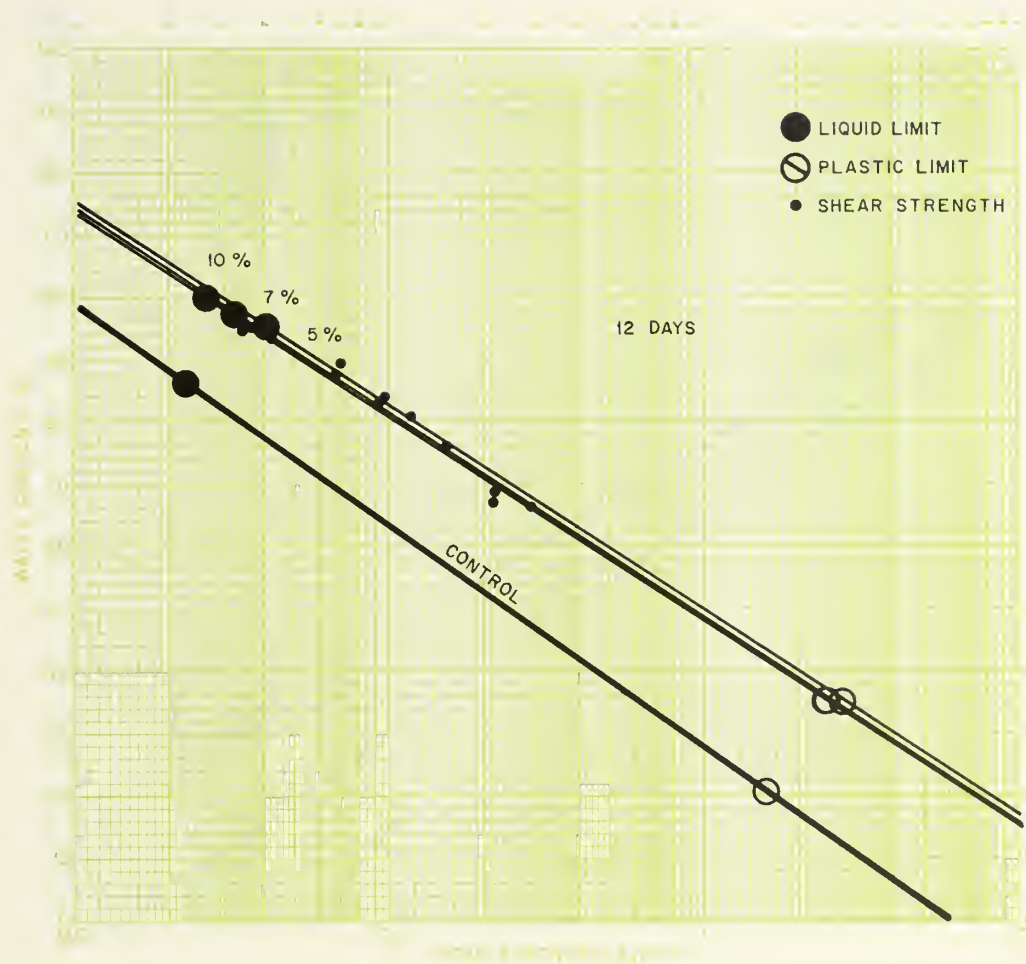


Figure 18. Shear curves for Diablo clay treated with 5, 7, and 10% HF

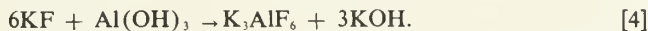
The most readily available source of these cations is the exchange surface of the soil. Most of the CEC of Diablo clay occurs within the expanding clays smectite and vermiculite. If fluosilicates formed from all exchangeable cations, only 173 meq (3 meq F/meq of cation  $\times$  57.7 meq/100 g soil) of HF would be needed for the reaction. This is equivalent to 3.5 g HF/100 g soil a 3.5% HF treatment), which is slightly less than the amount that appears optimal for this soil (Figures 17 and 18). Ho and Handy (1963) showed a relationship between the CEC of montmorillonite and the amount of calcium hydroxide needed to achieve maximum stabilization. A similar relationship with CEC appears likely for stabilization of smectites with HF.

The surface attack by HF and precipitation of insoluble fluosilicates may provide a rough surface (Raman and Jackson, 1965, p. 31) requiring extra water to overcome shear resistance. These data also support interlayer formation (Figures 4, 8, 9, and 10) as an important mechanism for increasing shear strength at all moisture contents.

### Potassium Fluoride

**Literature.** Apparently, potassium fluoride, KF, has not been tested previously for landslide stabilization. The chemical reac-

tion between neutral KF and soil results in precipitation of potassium fluoraluminate (Huang and Jackson, 1965):



The  $\text{Al}(\text{OH})_3$  is from clay mineral surfaces as well as from structural Al. In addition,  $\text{FeOOH}$ , structural Fe, and other Fe compounds react to form  $\text{K}_2\text{FeF}_6$ , potassium fluoroferrate. Unlike hydrofluoric acid, KF does not react with Si to form fluosilicates. Quartz, for example, is unaffected by neutral KF (Huang and Jackson, 1965). The physical changes produced by KF treatment should involve cementing agents produced with Al and Fe instead of Si. This should give additional insight into the mechanism for improving the shear strength of soil smectites.

**Treatment.** We found that potassium fluoride immediately increased the LL, PL, and shear strength of Diablo clay (Figure 20). These effects contrast with the effects of other soluble salts such as KCl (Figure 11). As explained earlier, KCl decreases the LL and high-moisture strength because the high ionic strength of soil porewater results in the collapse of expanding clays. KF, on the other hand, must expand these clays—that at least would explain how it produced the increases in LL and shear strength (Figure 20). Also, with KF, the initially high ionic strength of soil porewater must decrease rapidly, because

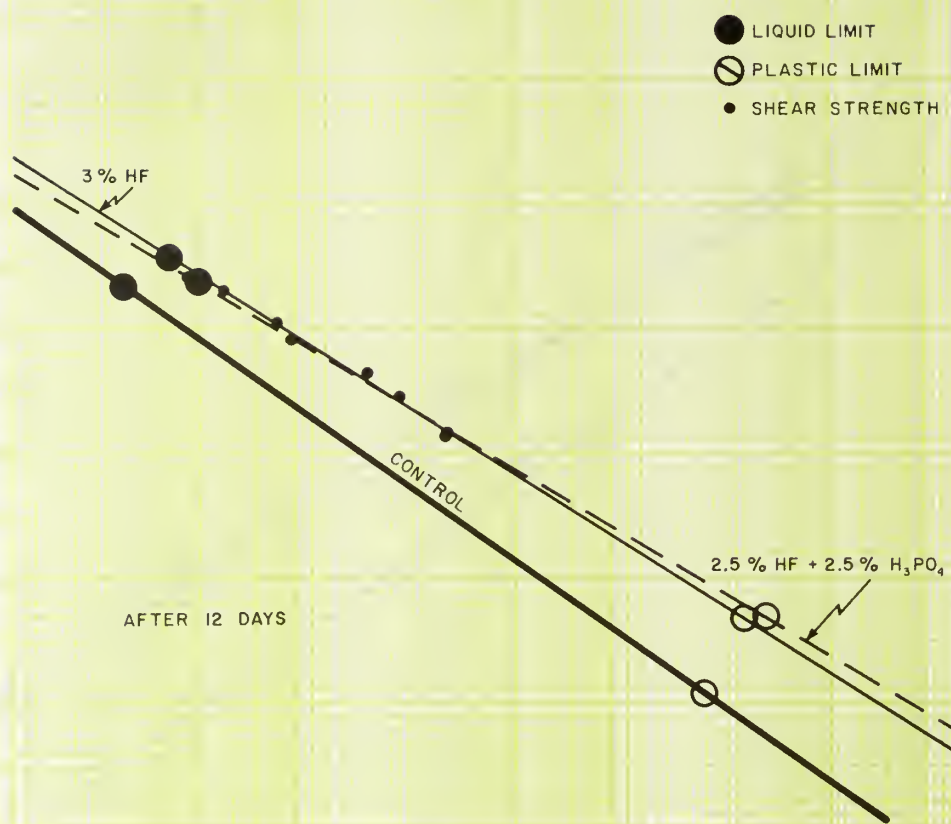


Figure 19. Shear curves for Diablo clay showing the inability of phosphoric acid to influence the strength produced by HF

the reaction products, fluoraluminate and fluorferrate, precipitated within 30 minutes (Huang and Jackson, 1965, p. 662).

Huang and Jackson (1965) showed an electron micrograph depicting the irregular surface of muscovite after treatment with KF. Similarly, KF probably attacks smectite surfaces to remove Al and to precipitate fluoraluminate. Either this precipitate or the surface roughness could be responsible for shear strength increases. The liquid limit and shear strength decreased after leaching the KF-treated soil (Figure 20). The LL decreased to 97, the same value found for KCl-treated soil after the excess salt was leached away (Figure 11). It therefore appears that the original smectite structure has survived KF treatment with little more than an increase in potassium saturation. If surface roughness was a significant contributor to shear strength, it probably would have been unaffected by leaching.

At 25°C, the solubility of  $K_3AlF_6$  is 1.4288 g per 1000 g of saturated solution. At 0°C, it is 0.8604 g per 1000 g (Seidell and Linke, 1952). Given enough time, 2.6 liters of water would be sufficient to dissolve the precipitated fluoraluminate from 100 g of Diablo clay that had been treated with 5 g of KF (that is, 3.71 g  $K_3AlF_6$  is formed for each 5 g KF). Ten liters of water were needed to remove the fluoraluminate and to disperse the KF-treated sample. It is concluded that fluoraluminate and fluorferrate precipitates probably are responsible for the increases in LL and shear strength.

A disadvantage of this treatment is the release of as much as 1429 ppm of  $K_3AlF_6$  in the leachate from the treated soil. Streams draining a treated area would contain up to 630 ppm fluorine in the water. This would have to be diluted up to 250 times in order to be at recommended levels for human consumption. If dilution were accomplished by runoff from untreated areas, no more than 0.4% of the soil in a watershed could be treated in this way.

As to the permanence of the treatment, a rainfall rate of 20 inches per year (50 cm) would remove no more than 65 g of fluoraluminate from each square foot (929 cm<sup>2</sup>) of landslide surface. A slide given a mass treatment to a depth of 5 m at the 5% rate of application would contain a maximum of 27,500 g of fluoraluminate for every square foot that was treated [assuming a bulk density of 100 pcf (1.6 g/cm<sup>3</sup>)]. It would take over 800 years to remove all of the fluoraluminate from the soil, assuming that half of the rainfall appears as drainage water. A KF-treated slide plane 0.5 m thick would survive about 80 years under the same assumptions. The longevity would be considerably less if the slide plane carried more than its share of drainage water.

**Concentration.** The effect of concentration was studied at five different levels between 1 and 10% KF (Figures 21 and 22). Five percent proportions of KF appeared to be optimum for increasing the shear strength of Diablo clay. However, 3% was



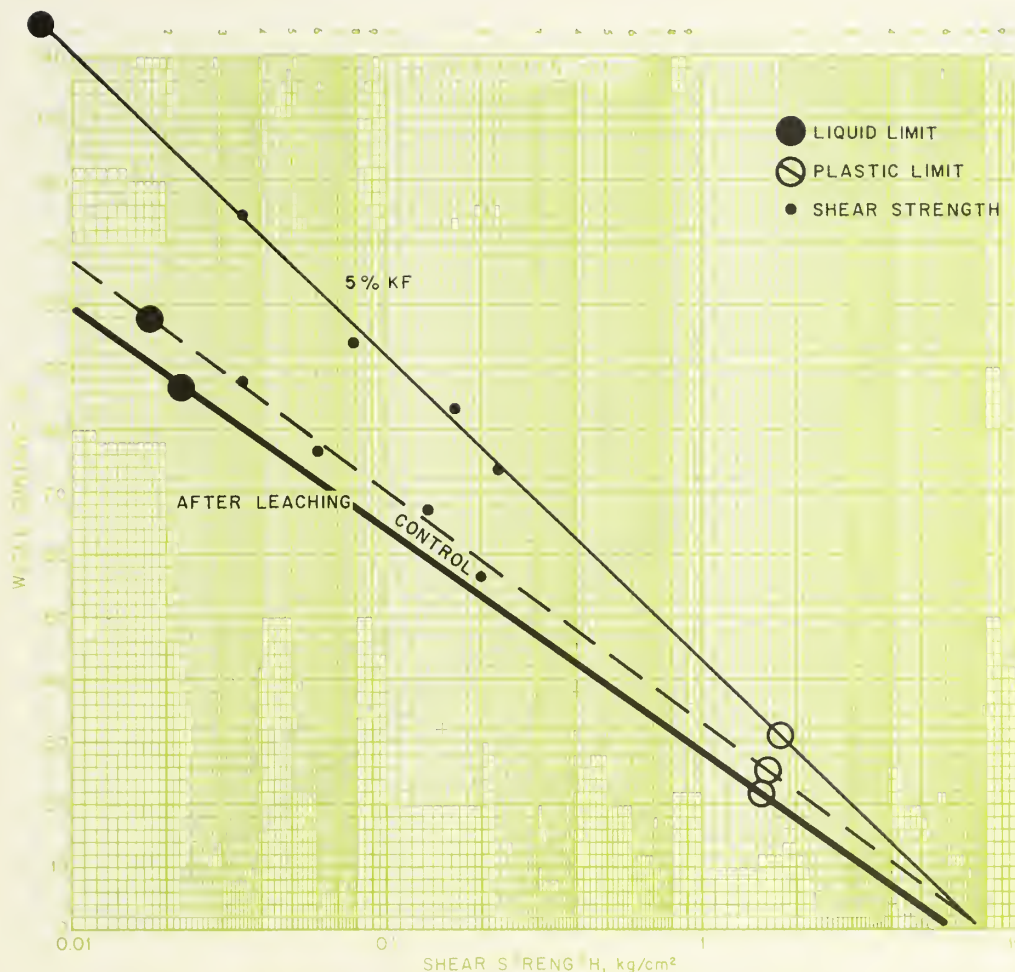


Figure 20. Shear curves for Diablo clay treated with 5% KF

only slightly less effective and would be a cheaper application (Figure 21). Reducing the amount to only 1% would produce very little improvement in strength but increasing the amount to 7% was counterproductive (Figure 22). Increasing the amount of KF to 10% actually decreased the LL and the high moisture shear strength. The reasons for these effects should become clear in the following discussion.

One percent KF increased the LL from 86 to 95 while increasing the shear strength only slightly (Figure 21). On the other hand, 3% KF increased the LL to 127. The 2 g of KF added after the initial 1% (1 g/100 g soil) contributed most of the strength gains observed. Changing the amount of KF from 3 to 5 g produced further, but less effective gains in strength (Figure 21). From data of Huang and Jackson (1965, Figure 2), it appears that expansive clays exhibit an initial resistance to destruction by KF (reaction 4). KF probably reacts first with the easily available Al and Fe on the external surfaces of soil particles. The internal surfaces of expansive clays are attacked only after the KF concentration increases. Perhaps, the strength increases only after the fluoraluminate begins to precipitate in the interlayer spaces of the smectite.

The counterproductive effects of 7% and 10% KF treatments (Figure 22) can be explained by the presence of excess KF (Figure 23). To demonstrate this, most of the excess KF was removed from the soil as follows: One hundred grams of soil

treated with 10% KF was mixed with 2.4 liters of water. After flocculation, the clear liquid containing the highly soluble KF was discarded. On the basis of its solubility (1.4 g/l), less than 3.3 g of fluoraluminate could have been removed along with the excess KF. This process increased the LL from 69 to 121. Also, the shear strength curve is now similar to the one after treatment with 3% KF (compare Figures 23 and 21). It is obvious that excess KF masks the strength gains produced by fluoraluminate precipitation. Smectite expansion produced by the precipitate can be overcome by increases in ionic strength of the porewater.

The extent of the KF-soil reaction is limited by the types of Al and Fe minerals unique to each soil (Huang and Jackson, 1965). Excess KF will precipitate no more fluoraluminate unless some of the reaction products are removed. For example, if KOH was neutralized, the equilibrium would move to the right in equation 4.

*Effect of precipitation of fluoraluminate on the liquid limit.* Excess KF depressed the LL by collapsing the expansive layer structure. The results for 10% KF (5% excess KF) are similar to those for 5% KCl (compare Figures 22 and 11). Both treatments result in structural collapse that occurs for reasons mentioned previously. However, certain differences between KF and KCl treatment should be pointed out. The excess KF depressed

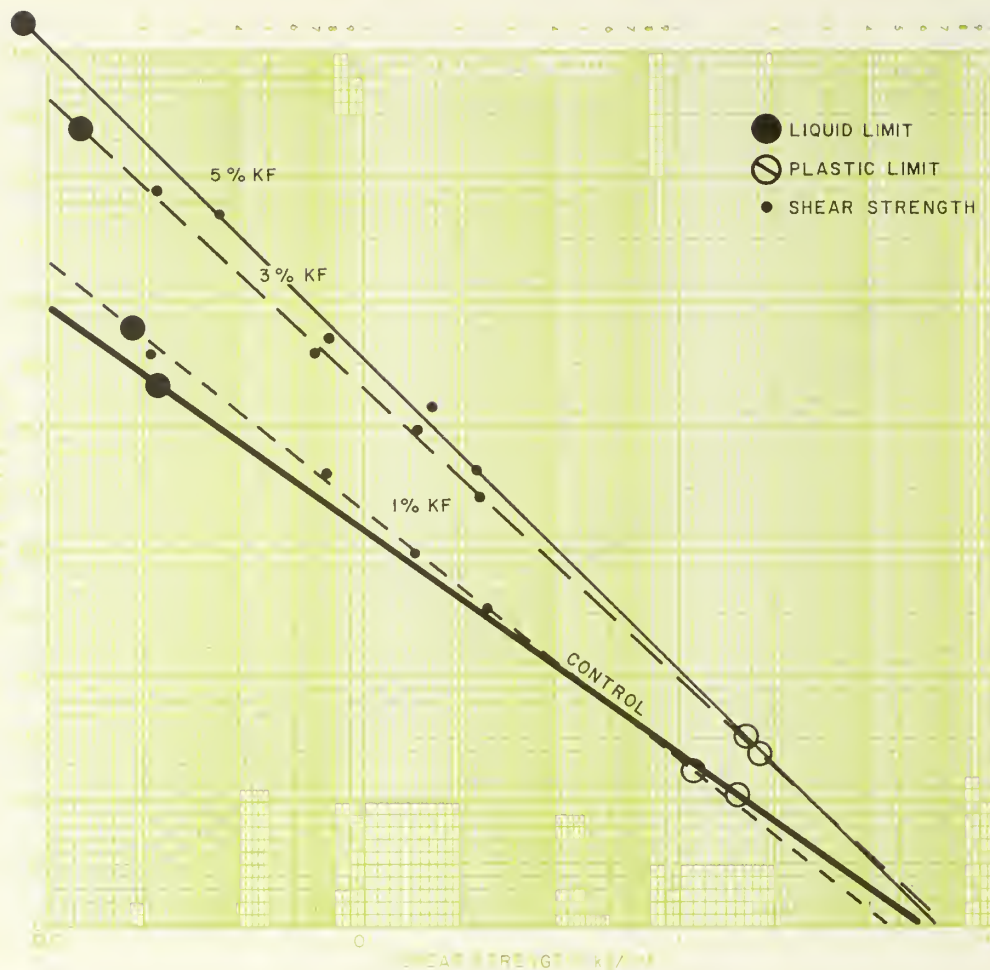


Figure 21. Shear curves for Diablo clay showing increases in strength as KF concentration increases from 1 to 5%

the LL to 69 while Na-, K-,  $\text{NH}_4^+$ , and Ca- chlorides all depressed the LL to 61 (Figure 13). Perhaps the lesser collapse of the KF-treated sample is indicative of precipitated fluoroaluminate between smectite layers. The shear strength of 10% KF-treated soil was  $0.029 \text{ kg/cm}^2$  while the strength of KCl-treated soil was  $0.045 \text{ kg/cm}^2$  at the LL (see Figures 22 and 11). As noted earlier, high salt concentration causes smectite to collapse. Corresponding increases in soil density may be responsible for the increases in shear strength at LL. Fluoroaluminate precipitation in interlayer spaces probably prevents complete collapse of smectites when excess KF is present.

*Time.* The reaction of KF to form fluoroaluminate continued somewhat for a period of three weeks (Figure 24). The LL increased from 127 to 140, but the PL did not change during this time. The shear strength increased at high-moisture contents and decreased at low-moisture contents according to extrapolated data. These changes are not too significant, and for practical purposes the development of strength by KF can be considered very rapid. Huang and Jackson (1965) showed that the reaction of 1NKF with soil was complete within 24 hours. The treatment is stable for at least three weeks in the absence of leaching.

## Conclusions

The soluble fluorides, HF and KF, produce rapid and substantial increases in shear strength at all moisture levels. HF does this by reacting with Si to form fluosilicates that seem to precipitate between the layers in smectites. The great insolubility of these fluosilicates prevents them from being leached away by rainfall. The reaction is complete in less than a week. Excess amounts of HF (greater than 5% for Diablo clay) are neither detrimental nor helpful to the newly developed shear strength. The disadvantages of using HF for landslide stabilization include its high cost and acute handling problems.

KF produces strength gains by reacting with Al and Fe to form potassium fluoroaluminate and fluoroferate. These compounds also appear to precipitate between layers in smectites. The reaction is almost complete within 30 minutes after application. Unfortunately, fluoroaluminate is slightly soluble ( $1.4 \text{ g/l}$ ) and would be leached slowly from the soil by rainfall. Unlike HF, however, excess amounts (greater than 5%) of KF are counterproductive because the unreacted KF increases the ionic strength of soil porewater, causing smectites to collapse and shear strength to decrease.



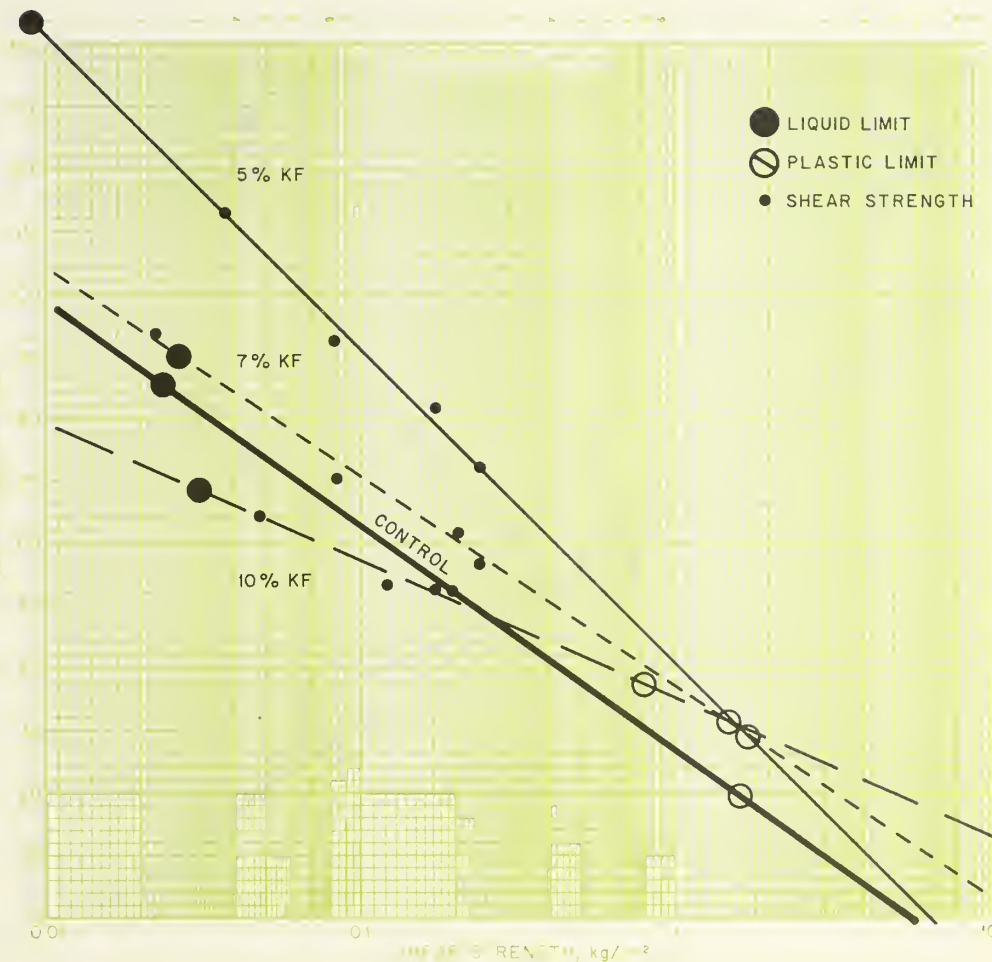


Figure 22. Shear curves for Diablo clay showing decreases in strength as KF concentration increases from 5 to 10%

## HYDROXIDES

Hydroxides furnish hydroxyl ions that increase soil pH and attack the surfaces of most soil minerals. This attack is most rapid with the smallest particles and with the least crystalline materials that have the greatest surface area. Calcium hydroxide is lime,  $\text{Ca}(\text{OH})_2$ , the most successful soil stabilizer ever used. Lime combines with Si and Al from the soil to form cementitious compounds that bind soil particles together. The most noticeable result is a drastic reduction in soil plasticity and expansion. Whether or not calcium hydroxides or other hydroxides can be used to increase shear strength in landslides is still an open question.

### Barium Hydroxide

**Literature.** Ten percent barium hydroxide,  $\text{Ba}(\text{OH})_2$ , increased the unconfined compressive strength of Wyoming montmorillonite from 19.4 to 39.9 kg/m² after 30 days at 100% relative humidity (Ingles, 1970). Because barium is similar to

calcium in its chemical characteristics, we decided to see if barium hydroxide reacts when applied to soil as calcium hydroxide does.

**Treatment.** Barium hydroxide increased the shear strength of Diablo clay at all moisture levels (Figure 25). These increases in strength were especially noticeable at low moisture levels. There were only slight decreases in LL and increases in PL. These physical properties were unchanged after 12 days of contact.

### Calcium Hydroxide

In this study, calcium hydroxide is referred to as lime. It should not be confused with other materials also referred to as lime, such as calcium carbonate,  $\text{CaCO}_3$ ; quick-lime,  $\text{CaO}$  (which forms  $\text{Ca}(\text{OH})_2$  upon addition of water); or dolomitic limestone,  $\text{MgCa}(\text{CO}_3)_2$ . Calcium hydroxide is used widely for stabilizing soils in road construction. It was probably the first chemical used for soil stabilization, because there is evidence of its use in ancient times (Ho and Handy, 1964).



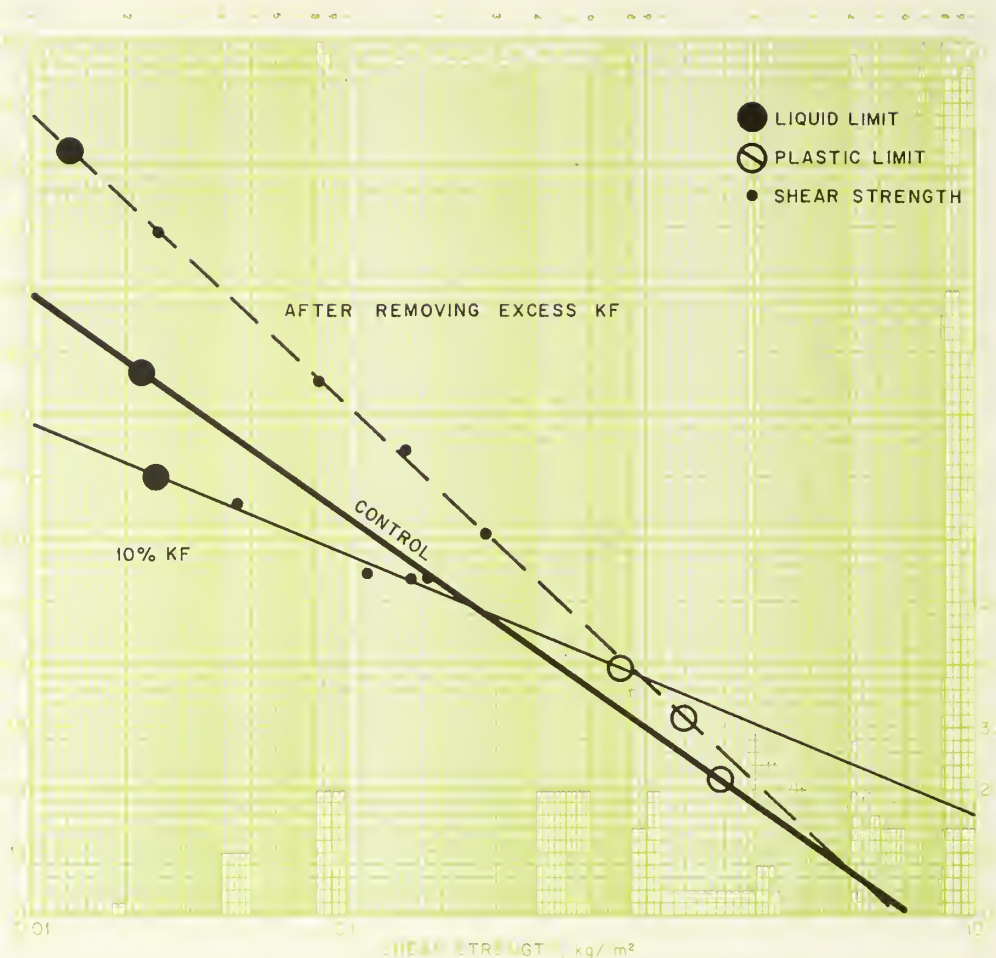


Figure 23. Shear curves for Diablo clay after treatment with 10% KF

Three important reactions can be observed when lime is added to smectitic soil: (1) rapid lime adsorption; (2) slow cementation, and (3) carbonation.

**Rapid adsorption reaction.** The plastic limit of smectite increases instantaneously when lime is added. The liquid limit decreases, and the result is often a four-fold reduction in the plasticity index (Anonymous, 1972).

The high PL of lime-treated soil may indicate "occlusion of free water within flocs" (Ho and Handy, 1964). Prikryl and Esterka (1960) were the first to conclude that lime was physically adsorbed on clay surfaces. The amount of calcium hydroxide adsorbed corresponds to the "lime fixation point" and represents about a monolayer of lime on the external surfaces of clay (Diamond and Kinter, 1965). The "lime fixation point" or "lime retention point" has been defined by Ho and Handy (1963) as the point beyond which increasing amounts of calcium hydroxide do not increase the viscosity of a soil. Lime retention occurs at a pH of 11.75. A "quick test" for lime requirement is the amount of calcium hydroxide required to hold the pH at 12.4 for one hour (Terlecky and others, 1975). Jones (1973) used a simple flocculation test to determine whether or not landslides were amenable to stabilization with lime. Ho and Handy (1963) showed a distinct relationship between the cation exchange

capacity of montmorillonite and the amount of calcium hydroxide needed to achieve maximum stabilization.

Whether or not calcium hydroxide enters the interlayer space of smectites is still open to question. Diamond and Kinter (1965) suggested that "a slow, restricted entry of lime into the interlayer spaces of the clay may take place." However, Pettry and Rich (1971) observed no calcium hydroxide in the interlayer space of lime-treated montmorillonite. Unfortunately, the clay had to be washed with HCl to remove amorphous material that prevented development of an X-ray pattern. The acid probably would have removed any lime as well.

**Slow cementation reaction.** Rapid adsorption of lime is "accompanied by a slower pozzolanic cementation reaction whereby hydrated calcium silicates (tobermorite gel) and aluminates form at the expense of the lime and montmorillonite. The newly formed silicates in particular are cementitious, and resemble those formed in hydrating portland cement" (Handy and Williams, 1966). Lime added to quartz produces tobermorite gel. Lime added to kaolinite, montmorillonite, or mica produces tobermorite and  $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 13\text{H}_2\text{O}$ , hydrocalumite (Diamond, White, and Dolch, 1964). Hydrocalumite is a double hydroxide isomorphous with its Mg analog, hydrotalcite (Taylor, 1973). Hydrotalcite is similar to the octahedral sheet in montmorillonite and chlorite.

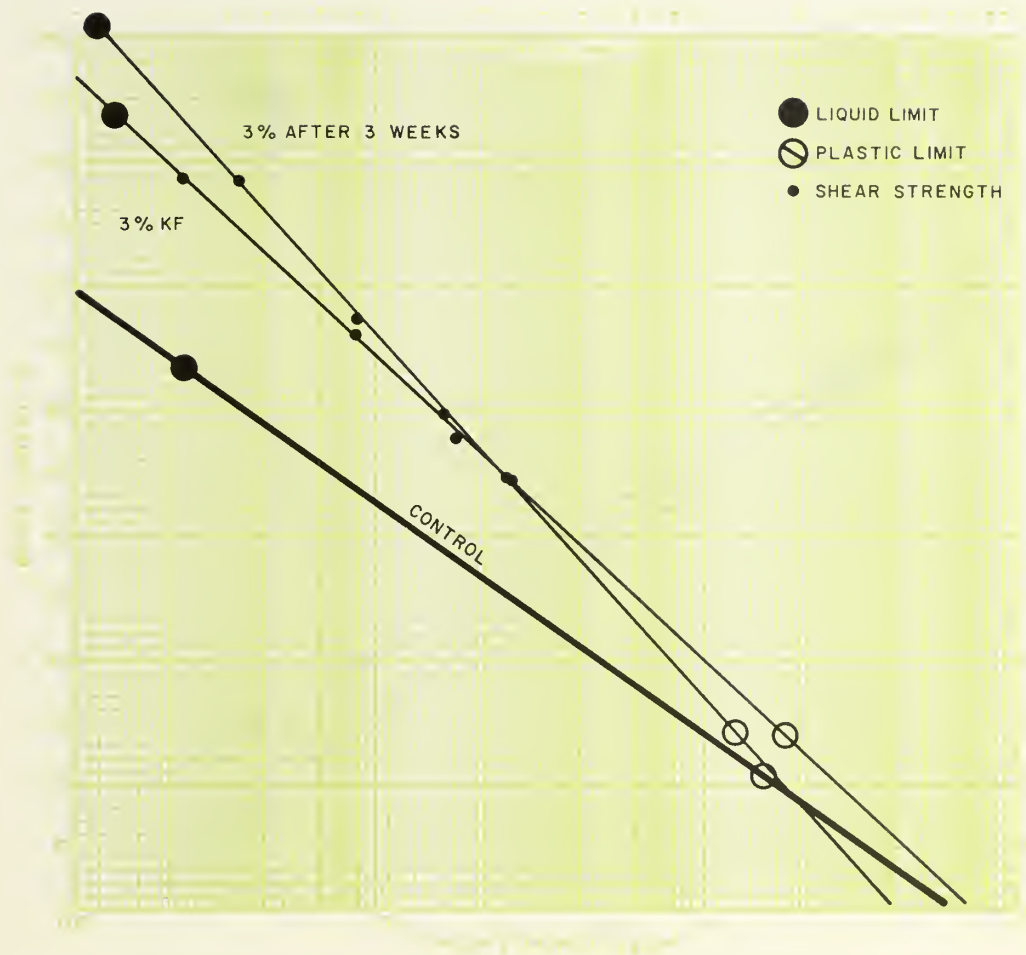


Figure 24. Shear curves for Diablo clay after three weeks contact with 3% KF

Because the cementation agglomerates silt particles, it decreases the amount of less-than-40-mesh size particles (Anonymous, 1972). The residual cores of clays retain complete crystallinity (Diamond, White, and Dolch, 1964). The reaction is exceedingly temperature dependent. Eades, Nichols, and Grim (1962) recommend treatment in the early part of summer. NaOH speeds the reaction of lime with soil, but aluminum chloride diminishes the effect of lime by neutralizing calcium hydroxide (Davidson, 1961). Also, lime doesn't work well as a stabilizer in the presence of large amounts of organic matter or sulfates (Ingles, 1968).

**Carbonation reaction.** Calcium hydroxide eventually reacts with carbon dioxide in air to form calcium carbonate. Even analytical grade  $\text{Ca}(\text{OH})_2$  has small percentages of  $\text{CaCO}_3$ , diluent that is ineffective in changing the physical properties of soil.

Petty and Rich (1971) noted the formation of calcium carbonate in soil even after successful treatment with lime. Slow air drying allows carbonation to occur through reaction with the  $\text{CO}_2$  present in air (Ingles and Metcalf, 1972, p. 128). Air drying a lime-treated soil for 14 days produced calcium carbonate but no Ca-silicate (Goldberg and Klein, 1952). Up to 71% of the lime was carbonated, but total carbonation was never achieved.

Calcium carbonate had no effect on the liquid limit of quick clay (Torrance, 1975). Talme (1968) found that calcium carbonate (and sodium bicarbonate) produced very little change in shear strength of soil. On the other hand, calcium carbonate initially decreased the shear strength of quick clay containing trivalent iron and aluminum (Moum, Sopp, and Loken, 1968). In general, "Carbonation is probably a deleterious rather than a helpful phenomenon in soil stabilization" (Diamond and Kinter, 1965).

**Use for landslide stabilization.** Lime adsorption may reduce plasticity, but according to Thompson (1967) only the slower pozzolanic reaction is responsible for strength increases. The unconfined compressive strength of Wyoming montmorillonite increased from 270 to 1680 psi after contact with 10% lime for 30 days at 100% relative humidity (Ingles, 1970). Tensile strength increases, but permeability is said to decrease (Anonymous, 1972). Fossberg (1965) found a long-term strength gain through increases in cohesion in lime-treated soil. Much of this increase is a result of interparticle cementation occurring at the expense of the weaker type of cohesion normally associated with great surface area. For example, Diamond, White, and Dolch (1964) found that the specific surface of lime-montmorillonite mix declined from 500 to 160  $\text{m}^2/\text{g}$  after the reaction.



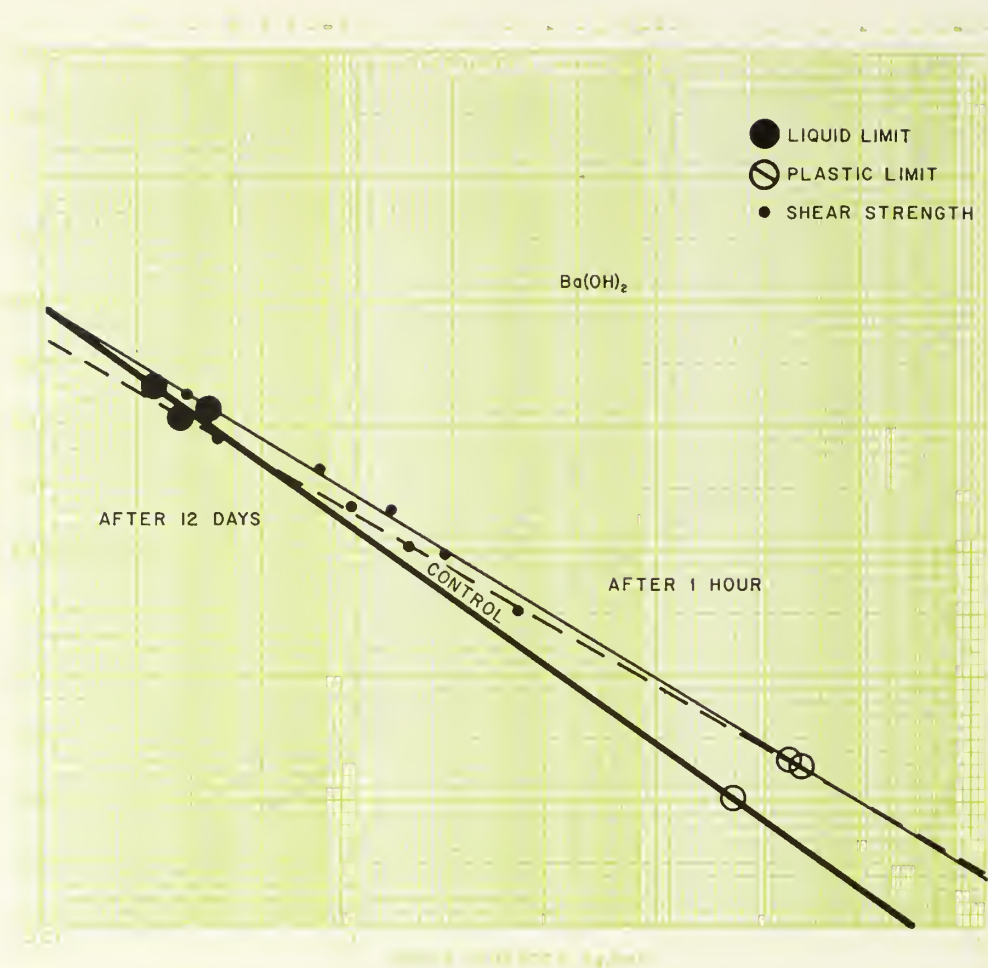


Figure 25. Shear curves for Diablo clay treated with 5% barium hydroxide

When 5% lime was added to a montmorillonitic clay containing sodium and calcium sulfate, the shear strength increased at all moisture levels (Kerr, Shroud, and Drew, 1971). That would imply an increase in LL which is at odds with all available evidence for lime-treated montmorillonitic clays. Lime was added to the list of chemicals for abatement of active soil slides (Graf and Kuhn, 1970).

Unfortunately, the low solubility of lime hampers its use for stabilizing landslides. Moum, Sopp, and Loken (1968) found that lime increased the shear strength of quick clay from 1.8 to 6.4 t/m<sup>2</sup> but only diffused 3 cm in 85 days. They say that it is difficult to calculate meaningful diffusion coefficients for lime, because it takes part in too many complicated chemical reactions in soils. The low solubility problem can be overcome by physically mixing lime with the soil, such as during the preparation of a roadbed over expansive soils.

Because physical mixing is impractical for landslide stabilization, other methods of achieving soil contact must be used. Handy and Williams (1966) devised a method to stabilize a landslide that occurred on fill. They bored 15 cm diameter holes on 1.5 m centers and put 25 kilograms of quick lime into each hole. Water was then added to each hole in order to hydrate the quick lime. The slide plane was within 3 m of the surface; 500

holes were drilled, and the area treated was about 2700 m<sup>2</sup>. The resulting lime content of 1% was considered to be adequate based upon mineralogical data for that soil. Physical and chemical tests of soils near the houses, as well as measurements of foundation displacement indicated the abatement of the slide, while adjacent houses on untreated fill continued to move. The cost was several thousand dollars, but this was only 10% of the depreciation sustained by the property as a result of the slide. A contrary view of lime stabilization was given by Moum, Sopp, and Loken (1968). They claim that Handy and Williams (1966) achieved stabilization merely from the drying out effect of CaO. They consider lime to be impractical for landslides.

Actually, lime has been used successfully in other localities. Jones (1973) used lime to stop the movement of some landslides in Brazil. He applied lime to the surface of the slides and on an area 7-15 m outside the crown and flanks. Particularly heavy applications of dry lime or slurries were made in the main scarp cracks and other open cracks in the slides. Jones used 3-5 tons of lime per acre. The solubility of lime was sufficient to produce calcium carbonate deposits at outlets to pipes draining landslides. Vegetation was lush. Landslides have been stabilized for more than two years with this treatment. In regard to lime treatment, Jones (1973) adds a word of caution however: "The



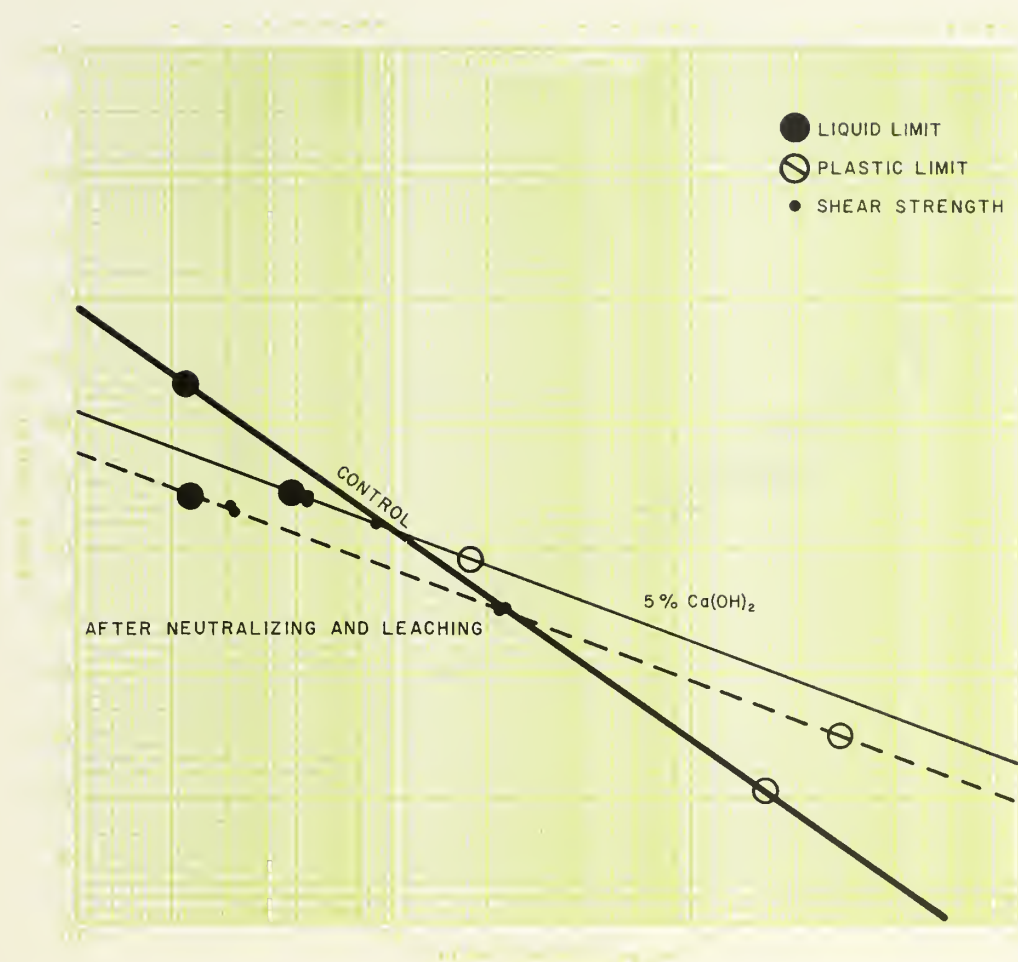


Figure 26. Shear curves for Diablo clay treated with 5% calcium hydroxide (lime)

possible effect of applying lime to unstable or potentially unstable slopes without providing sub-surface drainage is unknown. Unless a system of groundwater escape is provided, stability conditions within the slopes could conceivably become more hazardous with lime treatment than without it." This warning is well taken, as the next section shows.

**Treatment.** In our tests lime increased the shear strength of Diablo clay at moisture contents less than 62%, but decreased it at higher moisture contents (Figure 26). This substantiates Jones' (1973) suspicions about providing adequate drainage for lime-treated landslides. The PL increased dramatically from 21 to 58, while the LL decreased from 86 to 69. This resulted in an 85% decrease in soil expansivity, as measured by a decrease in the PI from 65 to 11.

Neutralizing the lime-treated sample with HCl followed by leaching with distilled water caused the PL to decrease from 58 to 30 (Figure 26). This also decreased the shear strength without changing the LL. These results must be considered in light of the three main reactions that occur in lime treated soils: (1) adsorption; (2) carbonation; and (3) cementation.

**Effect of rapid adsorption.** The rapid increase in PL from 21 to 52 is typical of successful lime stabilization on soils containing

smectites (Figure 27). The PL was 52 after 7 minutes contact with Diablo clay, and it remained at 52 for at least 10 hours after the initial contact with lime. Lime adsorption increased the shear strength for Diablo clay at moisture contents less than 74% (Figure 27). It also reduced the LL from 86 to 76.

Some of this reduction in LL probably resulted from an increase in ionic strength of soil porewater. Neutral chlorides, including calcium chloride, gave an LL of 61 at the 5% concentration level (Figure 13). Acidic chlorides had higher LL values, presumably because hydroxylation prevented a more complete collapse of the smectite. Perhaps calcium hydroxide adsorption between smectite layers prevented the LL from decreasing to 61.

**Effect of carbonation.** Whenever calcium hydroxide is exposed to air, the following reaction occurs:



When the lime-soil mixture is kept moist, the reaction is limited by the quantity of carbon dioxide. When excess calcium hydroxide is present, the pH is greater than 10. The pH of Diablo clay was 11.7 immediately after the 30-day treatment with lime (Table 4, sample 31/74). When a similar sample (522/72) was air dried slowly for a period of six months, the pH dropped to 8.3,

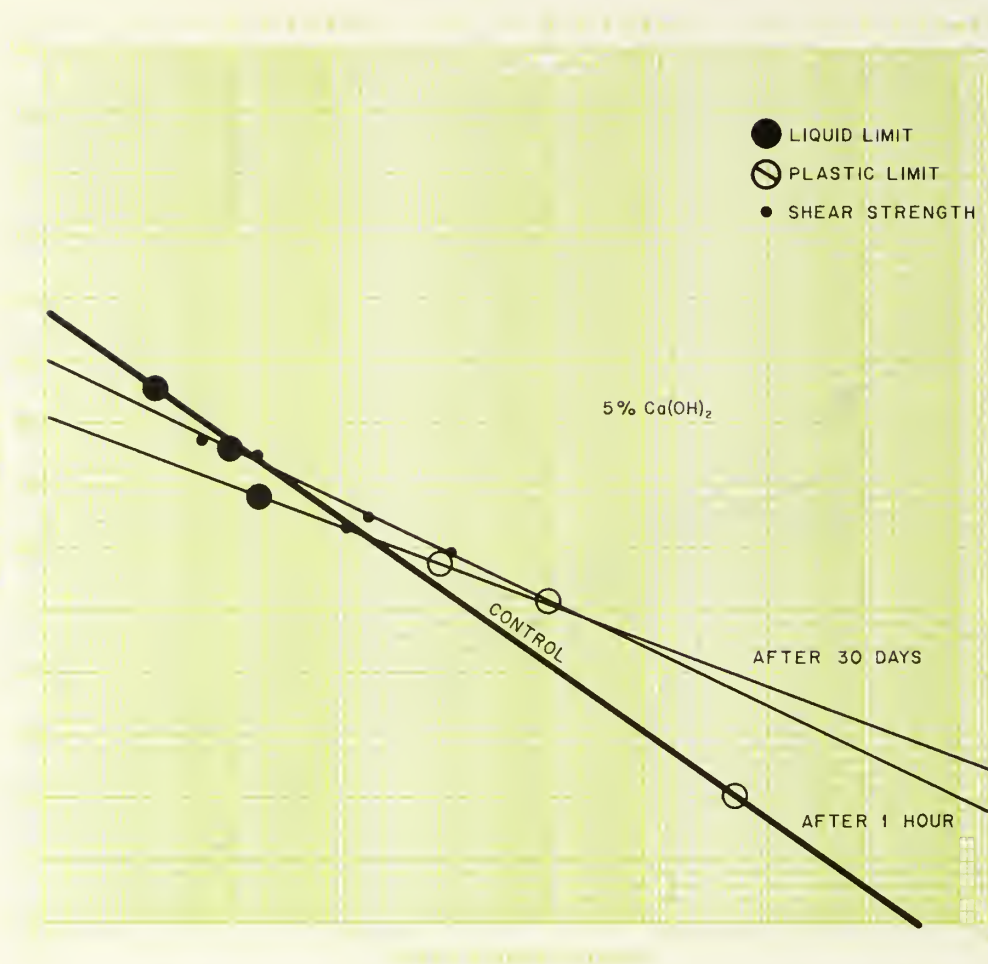
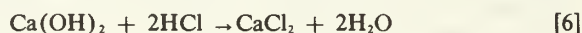


Figure 27. Shear curves for Diablo clay treated with 5% calcium hydroxide after one hour and after 30 days of contact

and 4.67%  $\text{CaCO}_3$  appeared as a result of reaction [5]. The PL dropped from 58 to 34. In another experiment, a fresh, lime-treated sample was rapidly air dried for 15 minutes. This caused the PL to drop from 52 to 47.

The excess calcium hydroxide in moist samples also reacts with  $\text{HCl}$  as follows:



This is further evidence for the presence of calcium hydroxide in treated soil after a 30-day contact period. Sample 32/74 was titrated with 94 meq of  $\text{HCl}$  to achieve a suspension pH of 7 (Table 4). This represents 3.48 g of calcium hydroxide. A small amount, 0.34 g, of calcium carbonate diluent was detected in the reagent grade calcium hydroxide by a method in which much lower pH's are used (Bundy and Bremner, 1972).

Sample 523/72 (Table 4) was neutralized after slow air drying. This sample required only 11 meq to attain a pH of 7 in suspension. This probably resulted from a small amount of  $\text{HCl}$ -attack on calcium carbonate (0.52 g), rather than from the

presence of calcium hydroxide (compare the carbonate contents of samples 522/72 and 523/72 (Table 4). The pH values (less than 10) of these air dried samples also indicate equilibrium with carbonate rather than hydroxide.

The addition of 6.75 g of pure calcium carbonate (equivalent to 5 g of calcium hydroxide after carbonation) to 100 g of Diablo clay did not change the PL (Figure 28). The LL decreased from 86 to 76, as in the calcium hydroxide-treated sample. The shear strength at low moisture contents remained unchanged by calcium carbonate, but the drop in LL was accompanied by a slight drop in the high moisture strength. Apparently, calcium carbonate contributes nothing to the shear strength of remoulded samples in which the weak cementation bonds produced by calcium carbonate would be broken easily during preparations for the shear test.

Removal of calcium hydroxide by either carbonation or neutralization reduced the PL from 58 to values between 30 and 34 (Table 4). Both the LL and most of the shear strength gains were unchanged by removal of excess calcium hydroxide. These permanent changes must have resulted from the cementation effect.



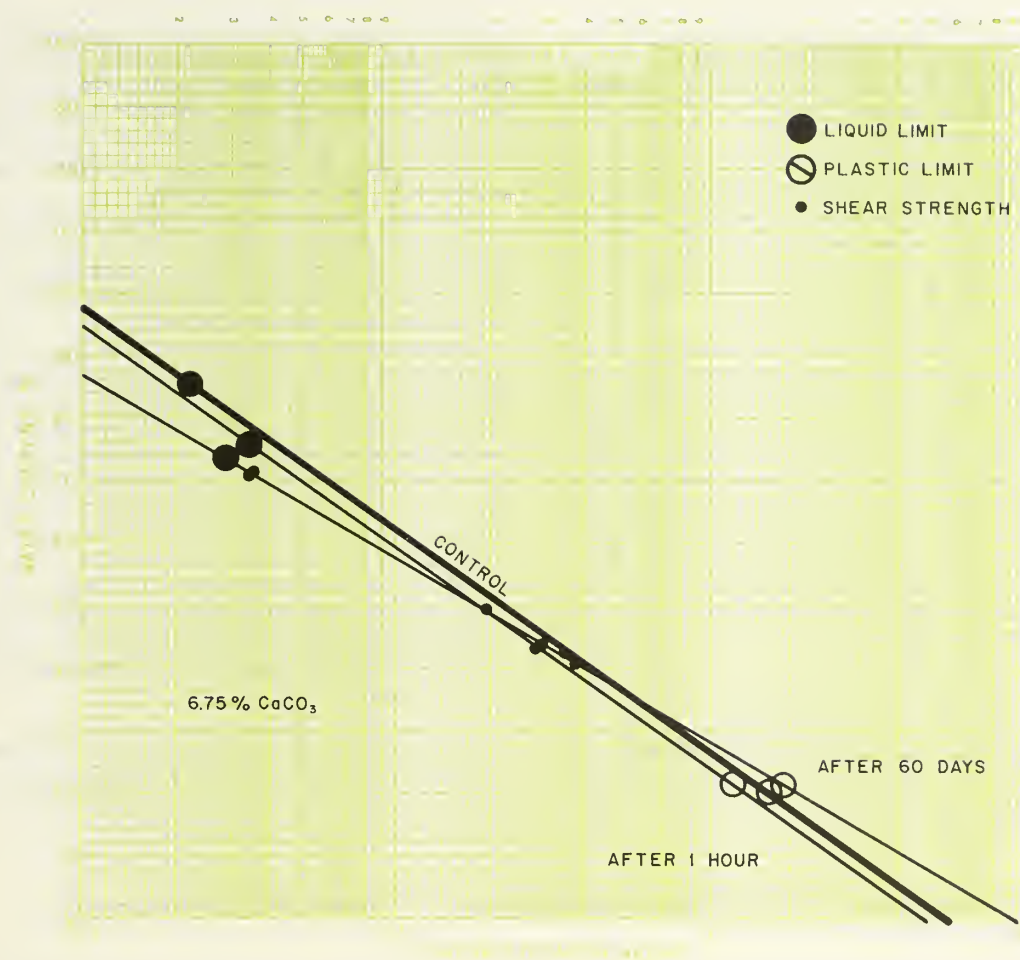


Figure 28. Shear curves for Diablo clay treated with 6.75% calcium carbonate after one hour and after 60 days of contact

**Effect of slow cementation.** The LL decreased an additional 7 percentage points from 76 to 69 after the initial adsorption of lime (Figure 27). Similarly, the PL increased an additional 6 points from 52 to 58. These changes are a result of either slow entry of lime into interlayer spaces (Diamond and Kinter, 1965) or, most likely, cementation. Between 1.18 and 1.45 g of the added calcium hydroxide could be considered "reacted  $\text{Ca}(\text{OH})_2$ ." It could not be titrated as either carbonate or hydroxide (Table 4). Thus, 25 to 31% of the lime added to Diablo clay produced cementitious products. These permanent changes in the shear curve (Figure 26) differ considerably from those produced by increases in calcium saturation alone (Figure 7).

Cementitious compounds such as tobermorite and hydrocalumite may be responsible for strength at low moisture contents. Except for only modest increases in PL, they act in ways similar to adsorbed lime, and similarly the cementitious compounds apparently do not enter interlayer spaces in smectites. If they did, increases in LL and shear strength at high moisture contents—like those found for hydroxy aluminum (Figure 4), HF (Figure 14, and KF (Figure 20)—would be expected.

Presumably, weathering of lime-treated soil will not bring about a return of the shear curve to its previous slope, even though plasticity is regained. In particular, lime treatment appears to be satisfactory for situations where reasonably good drainage can be maintained. The decrease in shear strength, illustrated here for high moisture contents, as well as the decrease in liquid limits, emphasizes that lime-treated landslides must be allowed free drainage. Indeed, the successful treatment of a landslide (Handy and Williams, 1966) was partially defeated after eight years of stability by ponding of surface water. This was due to runoff from an adjacent area (R.L. Handy, 1974, written communication).

### Potassium Hydroxide

**Literature.** Potassium hydroxide, KOH, treatment (Ingles, 1968) resulted in an initial strength loss. Treatment with 10% KOH decreased the unconfined compressive strength of undisturbed Wyoming montmorillonite from 19.3 to 5.7 kg/cm² after curing 30 days at 100% relative humidity (Ingles, 1970).



On the other hand, KOH increased the slaking stability of a micaceous clay that occurs in landslides of Ohio (Fisher, 1973). The amount of shrinkage was greater than for controls. The shear strength was not measured, however.

**Treatment.** In our tests, the effects of KOH treatment (Figure 29) were similar to those for lime (Figure 26). The LL decreased from 86 to 66 while the PL increased from 21 to 41, thus reducing the PI from 65 to 25. The low-moisture strength increased much as it did with the lime-treated sample. Leaching caused an increase in LL from 66 to 80 and a decrease in PL from 41 to 32.

The dry strength that results from this treatment may be high because of the formation of cementitious compounds, as was the case with the lime treatment. Presumably, potassium aluminates and silicates formed (Willoughby, Gross, Ingles, Silva, and Spiers, 1968, pp. 1388 and 1396) in addition to the calcium varieties resulting from replacement of natural calcium. These cementitious compounds apparently were not removed through leaching. The changes in shear strength that KOH produces suggest that it has promise as a substitute for lime. Much of the expansivity, however, may return as soon as leaching occurs. KOH is certainly far more soluble than lime, and therefore would be much easier to apply to landslides.

### Sodium Hydroxide

**Literature.** Sodium hydroxide, NaOH, gradually increased the compressive strength of kaolinitic soils (Ingles and Metcalf, 1972). However, 10% NaOH decreased the unconfined com-

pressive strength of undisturbed Wyoming montmorillonite from 19.3 to 10 kg/cm<sup>2</sup> after 30 days at 100% relative humidity (Ingles, 1970). Two products of NaOH attack on clay minerals are sodium silicate and sodium aluminate. Sodium aluminate is soluble at high pH, but eventually it forms insoluble aluminum oxide hydrates that act as cementing agents in the soil. Apparently, the sodium silicates counteract this effect.

Raman and Jackson (1965, Figure 3c) treated biotite mica with 3N NaOH for 30 minutes. After removing excess NaOH with distilled water, they showed precipitates of Fe- and Mg-hydroxides on biotite surfaces. These could be removed by a one-minute treatment with 1N HCl.

Unfortunately, NaOH may increase soil expansion. Ryther (1958) documented a case in which NaOH spillage caused foundations to move upward by 2 cm/year. Only 0.44% NaOH was found in the soil but 0.35% NaOH was found in the ground water. The effects of the spill were ameliorated by neutralizing the soil with sulfuric or hydrochloric acid. Hydrochloric acid was preferable because it corroded the concrete less than did sulfuric acid.

Normally, soil expansion is accompanied by increases in LL. However, Torrance (1975) reported decreases in LL for intermediate amounts of NaOH applied to quick clays. He attributed this to the dispersant effect of NaOH that would increase interparticle repulsion. Repulsion, however, would be expected to increase the LL of expansible clays.

**Treatment.** NaOH treatment did not significantly change the physical properties of Diablo clay when we applied the usual 5% amount (Figure 30). Only small increases in LL, PL, and shear

Table 4. Reaction products of 5% (126 meq/100 g) calcium hydroxide<sup>1</sup> in contact with Diablo clay for 30 days at 100% relative humidity.

CDMG No.	Subsequent treatment	pH	HCl titrant, meq	CaCO <sub>3</sub> , %	Equivalent <sup>3</sup> unreacted Co(OH) <sub>2</sub> , %	Reacted Ca(OH) <sub>2</sub> , g/100 g soil	Reacted Ca(OH) <sub>2</sub> as a percentage of amount added	Atterberg limits	
								LL	PL
31/74	None	11.7	nd <sup>2</sup>	nd	nd	nd	nd	69	58
522/72	Slowly air dried for six months	8.3	nd	4.67	3.21	1.45	31.1	70	34
32/74	Neutralized to pH 7 in suspension	8.7	94	0.35	3.48	1.18	25.1	68	30
523/72	Slowly air dried for six months and neutralized to pH 7 in suspension	7.9	11	4.15	3.23	1.43	30.7	67	32
485/72	Control	7.4	0	0.05	0	0	None added	86	21

<sup>1</sup> The 100 g soil samples were treated with 5 g of reagent grade calcium hydroxide equivalent to 4.66 g Ca(OH)<sub>2</sub> and 0.34 g CaCO<sub>3</sub>. Subtract 0.34% CaCO<sub>3</sub> from samples to get the amount of Ca(OH)<sub>2</sub> that reacted with CO<sub>2</sub> during the experiment.

<sup>2</sup> nd = not determined.

<sup>3</sup> This is the Ca(OH)<sub>2</sub> that did not form tobermorite or hydrocalumite. It formed CaCO<sub>3</sub> in air or could be titrated with HCl.

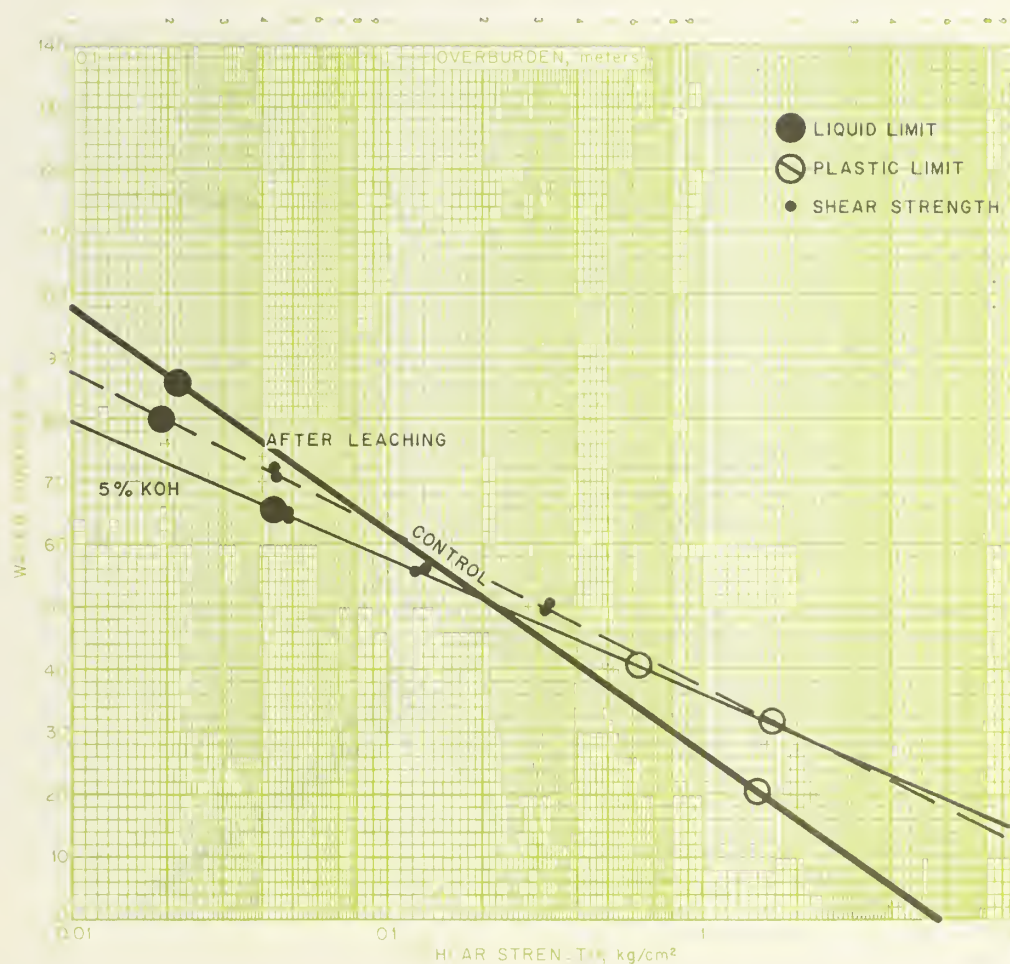


Figure 29. Shear curves for Diablo clay treated with 5% potassium hydroxide

strength resulted from the treatment. A possible reason for this involves the low solubility of most minerals in NaOH. For even the most soluble silicates, NaOH dissolves less than one gram of mineral per liter (Hashimoto and Jackson, 1960). In the 70 ml of water used, only 0.07 g of our 100 g sample of Diablo clay was dissolved initially. However, new aluminosilicate compounds may eventually precipitate from NaOH solutions, at which time additional soil minerals could be dissolved.

**Leaching.** Leaching the NaOH-treated sample dramatically increased the LL from 90 to 161 (Figure 30). There were corresponding increases in shear strength at moisture contents above the PL. The increased slope of the shear curve probably indicates an increase in cohesion rather than internal friction. This huge increase in LL represents a tremendous expansion of the smectite structure.

Such expansion could be brought about by the presence of hydrated Na ions between smectite layers. However, it has been shown that the addition of a similar amount of neutral salt, NaCl, did not increase Na-saturation of Diablo clay by more than 15% (Figure 12). Unless exchangeable Na is greater than 15%, the physical properties of smectites are unaffected.

Because Diablo clay is saturated naturally with Mg, Ca, Na, and K (Table 1), the addition of hydroxide would precipitate the

hydroxides of these elements. The less soluble hydroxides of Ca and Mg would precipitate according to the reaction:



The precipitation of the hydroxide would speed the sodium saturation of the clay. Subsequent leaching of the calcium hydroxide would reveal an Na-saturated clay. Magnesium hydroxide is too insoluble to be removed by leaching. Calcium hydroxide precipitation may be indicated by increases in PL for both KOH (Figure 29) and NaOH (Figure 30).

Complete removal of the newly precipitated calcium hydroxide may be indicated in the NaOH-treated sample. Leaching caused the PL of this sample to decrease from 41 to 32, not as low as the KCl treated sample (PL=23, Figure 13). Perhaps lime or its products are easily leached from NaOH-treated soil but remain in KOH-treated soil.

After leaching, the high LL of the NaOH-treated soil indicates that it is highly Na-saturated (Figure 30). The LL of the KOH-treated soil does not reveal high K-saturation (Figure 29). The PI of the NaOH-treated sample increased from 61 to 138 as a result of leaching, and the expansivity more than doubled. Obviously, the NaOH treatment would be counterproductive for use in reducing soil expansion. These data confirm the results of Ryther (1958).



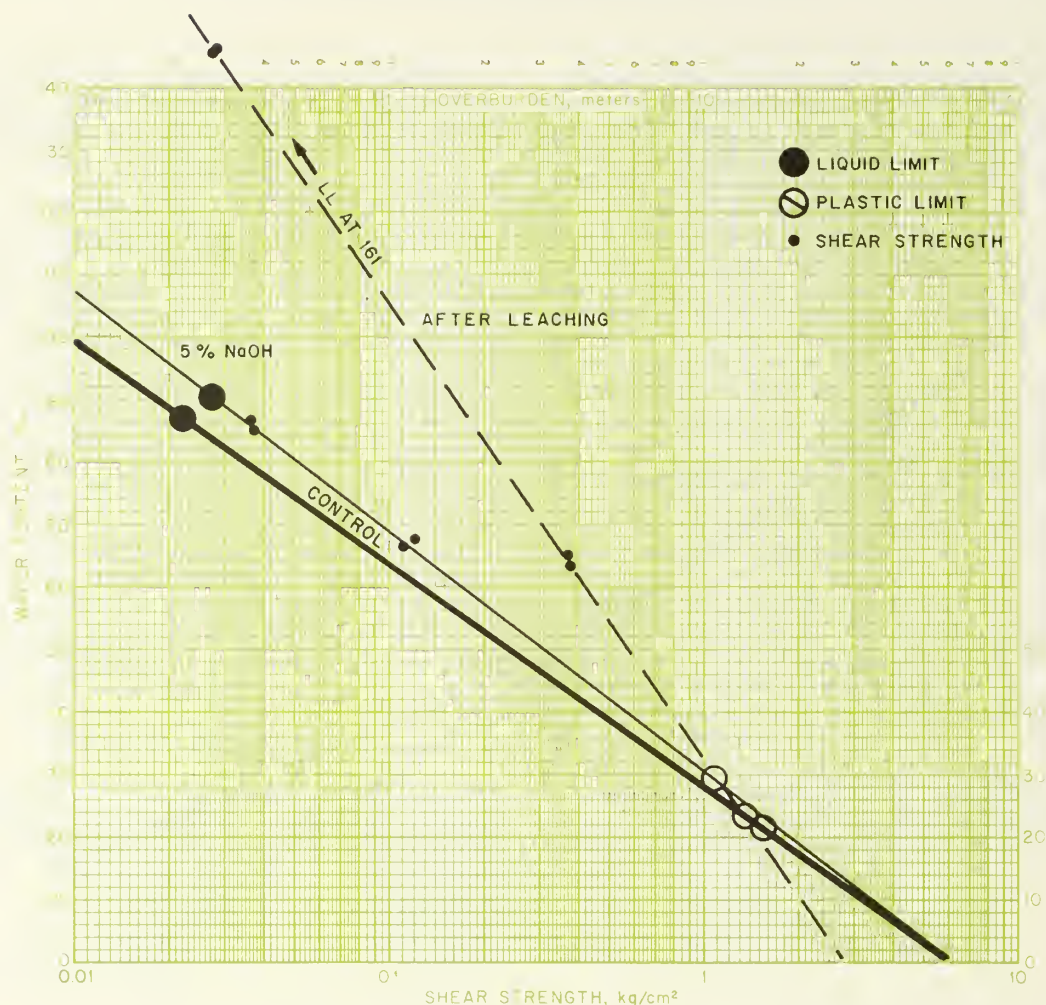


Figure 30. Shear curves for Diablo clay treated with 5% sodium hydroxide

Initially, NaOH treatment would produce only a slight improvement in shear strength. Subsequent leaching by rainfall would develop further increases in strength. Unfortunately, the reduction in ionic concentration in the pore solution also would decrease the permeability of the soil (Russell, 1961). This reduction in drainage might then allow the water content of the soil to increase even faster than the increase in shear strength. Depending upon the rate of drainage and water utilization by plants, such soils might show an overall gain in adsorbed water after several seasons. Even so, NaOH-treated Diablo clay would have to undergo an increase in water content (for example, from 50% to 78%) in order for the shear strength to decrease after treatment (Figure 30). Presumably, the shear strength would increase gradually while leaching occurs. If the moisture content also increased at the same time, the purpose of the NaOH treatment would be defeated. The relationships between these three variables should be studied in further detail.

### Conclusions

The hydroxides of Ba, Ca, and K increase the shear strength of Diablo clay while decreasing its expansibility. Calcium hydroxide adsorption produces a rapid and dramatic rise in the

plastic limit of smectitic clay. This adsorbed lime rapidly increases the shear strength at low moisture contents. About 1% of the lime (an amount about equivalent to the calcium saturation of the soil) then reacts with Si and Al to form cementitious compounds. These maintain the shear strength even after the adsorbed calcium hydroxide disappears. Excess calcium hydroxide is neutralized by soil acids or leached away by rainfall. It also reacts with carbon dioxide to form relatively inert calcium carbonate. Carbonation of lime is most rapid whenever the soil is dried in air. The cementitious compounds are highly insoluble, and they appear unattacked by HCl or leaching. Most of the changes in shear strength produced by lime are permanent. However, good drainage must be provided to avoid the low strength produced by excess pore pressure at high-moisture levels.

The hydroxides of Ba and K produce some effects similar to those produced by lime. NaOH, on the other hand, produces increases in shear strength and expansivity that continue to develop as the excess NaOH is leached away. In 5% proportions, NaOH appears highly effective in producing an Na-saturated or dispersed clay, but a neutral salt such as NaCl appears ineffective. Because strength development with NaOH requires leaching, adsorbed moisture also is expected to increase, thus offsetting strength gains.



## ORGANIC CHEMICALS

The effects of certain organic chemicals on the surface properties of clay were reviewed by Mielenz and King (1955). Ingles (1968) suggested the following organic chemicals as possibly useful as soil stabilizers: cetyl trimethyl ammonium bromide, *polyacrylamide*, polyvinyl alcohol, rosin, aniline-furfural and casein-formaldehyde. Incidentally, ingestion of 1/4 ml of aniline can cause poisoning (Ogilvie, Sheller, and Davidson, 1957). Organic chemicals have been used in patented procedures for stabilization of soils (Lyons, 1959a; 1959c; Kuhn, 1970). Na-stearate (soap) has been tested for its effects on soil properties (Talme, 1968). Polymethine (0.05-1%) added with calcium chloride (0.1-1%) has been successful for stabilizing soil, but it must be mixed in physically (Allberry and Hawkins, 1954).

### Plasticity

Organic cations can replace natural ions from clay, thus increasing the plastic limit and decreasing the liquid limit (Davidson, 1949a, p. 21). Octadecyl ammonium chloride decreased the PI of a soil from 13 to 3 when applied in 3% amounts (Davidson and Glab, 1949). Rosin amine-D-acetate decreased the PI of a soil to zero (Davidson, 1949b). Overall, Armac T appears the most promising organic chemical for reducing soil expansion. As an aside, the formation of kaolinite, a non-expanding clay, has been aided by the presence of an organic compound named quercetin ( $C_{15}H_{10}O_7$ ) (Hem and Lind, 1974). Quercetin slows the normal polymerization of Al at high pH (6.5-8.5). This produces the Al-O bonds needed for kaolinite instead of the Al-OH bonds that normally form at this pH.

### Strength

The organic cations make large areas of clay surface non-wettable, reduce cohesion, and increase the internal angle of friction. Ca- and Cr-base lignins are reported to give soils high strength (Matsuo, 1967).

A possible disadvantage of treatment with organic chemicals is a notable decrease in dry strength (Davidson, Demirel, and Rosauer, 1960). "Air-dry strengths are decreased by the addition of large organic cations whereas immersed strengths are greatly increased" (Nicholls and Davidson, 1957).

### Interlayering with Organic Cations

Formate and acetate salts of various amines will form complexes with montmorillonite (Rex and Bauer, 1964). These 6-18 carbon-amines enter the interlayer space in montmorillonite, thus producing clay-organo complexes with diagnostic x-ray spacings. Rex speculates that part of the results are explained by the removal of hydroxy aluminum polymer from montmorillonite surfaces. Shear strength and Atterberg limits were not evaluated by Rex, but Davidson (1949a) gives data that might be applicable to these amines.

A disadvantage of interlayering with organics is that partial displacement of  $Ca^{2+}$  ions by small alkylammonium ions actually may increase soil swelling (Greenland, 1965). Also, negatively charged organic compounds may cause dispersion of soil by blocking positively charged exchange sites and complexing polyvalent cations that flocculate clay (Greenland, 1965). It is possible for organic chemicals to improve the shear strength of aggregates while decreasing the shear strength of the soil as a whole.

## Permeability

Another area of interest to landslide stabilization includes the use of soil conditioners to control wind and water erosion as well as water repellency (Gardner, 1975; Blavia, Moldenhauer, and Law, 1971). For example, the tensile strength of montmorillonite films increased with increasing amounts of polyvinyl alcohol (Dowdy, 1973). As little as 0.5% polyvinyl alcohol doubled the tensile strength of Ca-montmorillonite films. Polyvinyl alcohol adsorbed on all surfaces of montmorillonite did not change the CEC (Greenland, 1965). Soil conditioners are applied only to the soil surface, and it is not known whether or not any of them might be used successfully to stabilize landslides.

A water-impermeable barrier can be produced in soil by 1-4% of certain polymers formed from the reaction between acrylamide and alkylidene bisacrylamide (Rakowitz, 1962). Physical mixing of Na-acid abietate is reported to stabilize and increase runoff from soil while allowing evaporation to occur (Miller, 1945). Phenoplastic resins have been injected into rather permeable fine sands (Caron, 1967), but would be of little use in most clayey materials.

On the other hand, permeability also can be increased with organic chemicals. For example, Monsanto used "Lytron" (vinyl acetate and maleic anhydride) for improving the filtration rate of a soil suspension by a factor of 50 (La Mer and Smellie, 1962). Polyvinyl alcohol increases rainfall acceptance when applied to surface soils (Stefanson, 1973).

## Biodegradability

Biodegradability has been of concern when organic compounds are added to soils (Valoras, Osborn, Letey, and Martin, 1973). There may be some question as to the durability and stability of organic compounds under soil conditions. Obviously, the persistence of organic compounds used to treat landslides is an important consideration. In general, the degradation of an organic compound decreases with decreasing moisture. However, most of the organic compounds used for soil stabilization are little affected by microbes (Brandt, 1972).

## Effect of Organic Chemicals

### ARMAC T

Armac T was selected as an example of the large, positively charged amines known to reduce soil plasticity (Davidson, 1949a). Armac T, though water soluble, had to be physically mixed with Diablo clay under the conditions of this experiment. The need for physical mixing should be considered a serious drawback for application to landslides, even if it was found beneficial for stabilization. There are, however, hundreds of organic compounds with numerous properties, and Armac T could never represent them all.

The results for Diablo clay are similar to those for the Edina subsoil of Iowa (Davidson, 1949a). The liquid limit decreased from 86 to 58 and the plastic limit increased from 21 to 32 after treatment with Armac T (Figure 31). These results, along with the decrease in slope of the shear curve, are very similar to those with soluble chloride salts. Davidson (1949a) found a decrease in overall shear strength with a decrease in cohesion but an increase in the angle of internal friction. A decrease in cohesion may be indicated in Figure 31 by a decrease in slope of the curve. An increase in internal friction may be indicated by an increase in strength at low moisture contents.

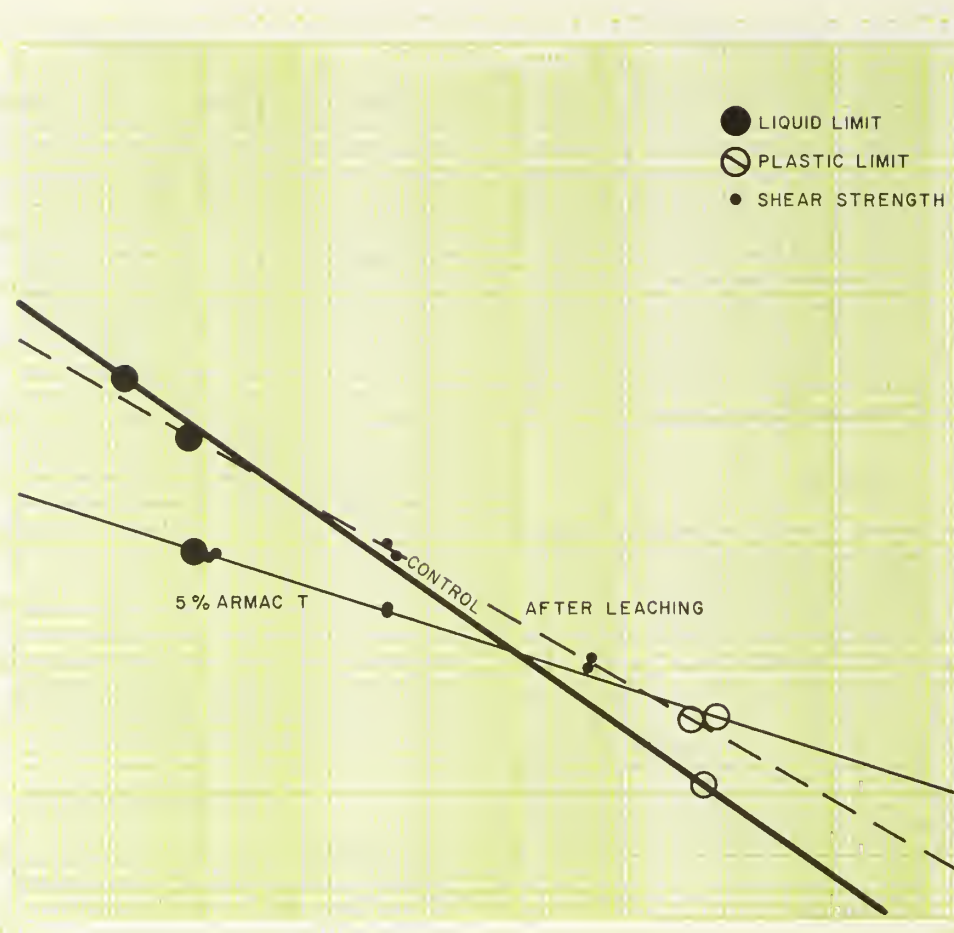


Figure 31. Shear curves for Diablo clay treated with 5% Armac T

The mechanism of the reaction between Armac T and montmorillonite involves an ion exchange between the natural Ca and Mg and the positively charged amine. The hydrophobic nature of these long-chain, fatty acids prevents water adsorption wherever they occur. For example, water adsorption decreased from 15% to about 1% when 5% amounts of Armac T were added to Edina subsoil (Davidson, 1949a). Thus, decreases in LL can be explained by prevention of water adsorption between clay layers.

Changes in PL cannot always be predicted. Davidson found both increases and decreases in PL and gives no explanation for it. He also found no significant changes in its physical properties after the treated sample was washed with water (Davidson, 1949a). However, this was not the case for Diablo clay. After leaching with 600 ml of water, the LL increased from 58 to 76. Seemingly, some of the cohesion was regained, and some of the original increase in dry strength was lost (Figure 31). Part of the Armac T remained, as evidenced by an LL lower than the control and dry strength higher than the control.

#### ETHYLAMINE HCl

Ethylamine HCl, like Armac T, reduced the plasticity of Diablo clay (Figure 32). The LL decreased from 86 to 50, which was

the lowest value found for any treatment. The PL increased from 21 to 34, and the PI decreased to 16, the lowest value measured for the plasticity index of treated Diablo clay. As was not the case with the Armac T-treated soil, the physical properties of Ethylamine HCl-treated soil returned to their original values after leaching. Ethylamine HCl was entirely leached from the sample, as evidenced by a return to all the original values for LL, PI, and shear strength. Compounds like ethylamine HCl may be soluble enough for treating landslides without physical mixing, but they are leached out just as easily.

#### HYDROXYLAMINE HCl

Hydroxylamine HCl, another large amine compound, wasn't nearly as effective as the other two organic compounds in decreasing soil plasticity (Figure 33). The LL only decreased to 80 while the PL increased to 31. As is common for treatments that increase the PL but do not decrease the LL significantly, the high moisture strength was not decreased. Leaching the hydroxylamine-HCl-treated sample returned the soil essentially to its original physical condition.



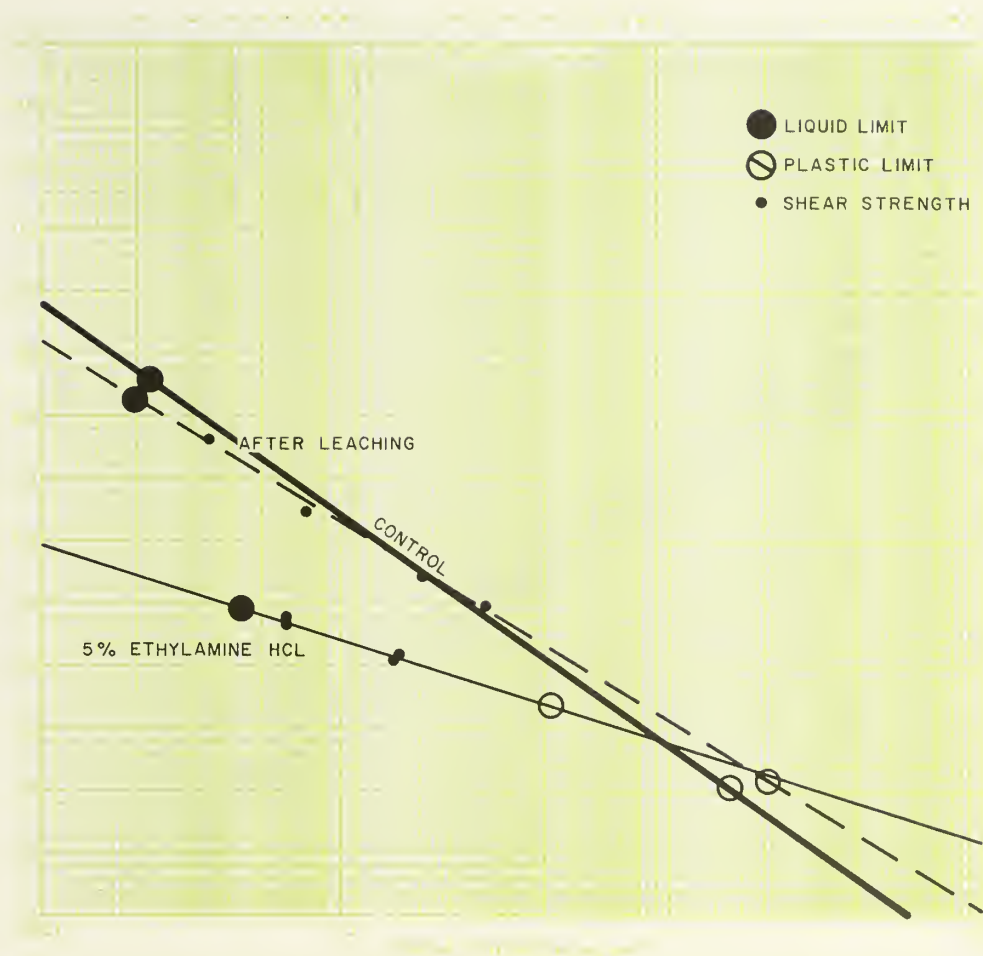


Figure 32. Shear curves for Diablo clay treated with 5% ethylamine HCl

## Conclusions

In general, large organic cations such as Armac T may be suitable for decreasing the expansive properties of soils. However, shear strength improvements appear only when moisture content is low. Davidson (1949a) found decreases in air-dry strength which he considered a measure of cohesion. On the other hand, the same soils showed an increase in the angle of internal friction. Shear curves probably overestimate the dry strength when cohesion is low.

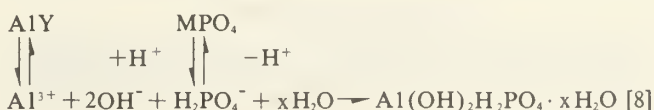
None of the three compounds seems especially desirable for landslide stabilization at the 5% level of application. Compounds that are soluble enough to dissolve in water and penetrate the landslide also are soluble enough to be leached by rainfall. However, there are thousands of organic compounds. Perhaps one will be found that is soluble in water, has a high affinity for montmorillonite, increases the shear strength at all moisture levels, and is resistant to leaching. The recently developed polyurethanes, such as the Japanese TACSS T-019, "would be superb for landslide stabilization since they are water-triggered polymerizing materials of very low viscosity. They are of course expensive" (O.G. Ingles, written communication, January 9, 1978).

Other aspects of landslide stabilization with organic chemicals were not investigated. One approach in particular needs further investigation. This involves changing the permeability of the soil surface. For example, coarse, noncohesive soils can produce landslides only after rapid penetration of rainfall. Anything that reduces the infiltration rate, such as a thin film of an organic chemical, might be of use in preventing landslides in certain soils, provided lateral seepage is prevented.

## PHOSPHATES

It is well known that phosphates react with soils to form insoluble precipitates (Hemwall, 1957). Under low pH conditions (less than 6) aluminum and iron phosphates form. Under high pH conditions (greater than 8) calcium phosphates form.

Hemwall and Scott (1962) have discussed the important reactions involved in phosphate stabilization of soils. The general reaction is:





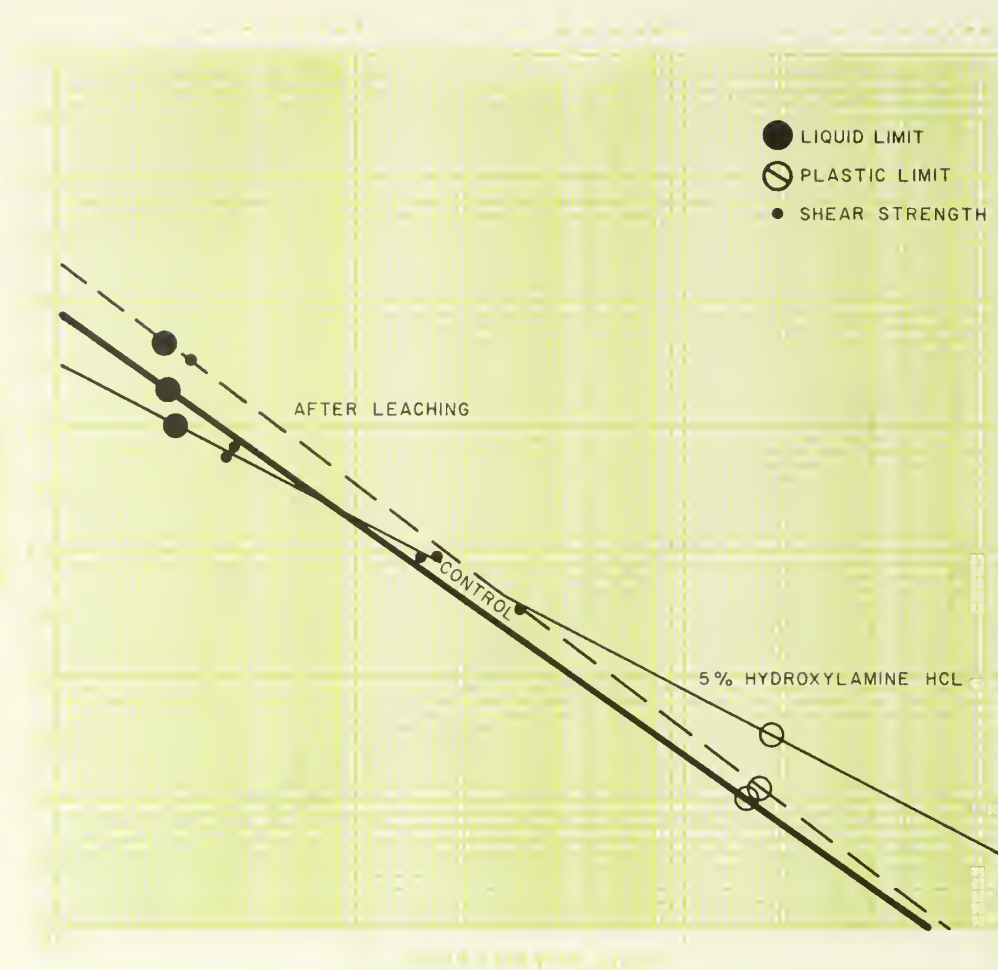


Figure 33. Shear curves for Diablo clay treated with 5% hydroxylamine HCl

AlY represents aluminum in clay or other minerals. Highly aluminous clays, such as kaolinite or chlorite, supply much more Al than do siliceous clays like montmorillonite. Thus, for example, the aluminous smectite, beidellite, should be more reactive than such siliceous smectites as montmorillonite.

Electron micrographs of reaction products of phosphates and clay minerals show actual dissolution of the clays, forming completely new phases (Kittrick and Jackson, 1956). The reaction product  $\text{Al}(\text{OH})_2\text{H}_2\text{PO}_4 \cdot x\text{H}_2\text{O}$  is hard and highly insoluble. This material, as with its iron analog, acts as a cementing agent that causes clay particles to bind together as though they were much larger silt or sand particles.

The physical properties of aluminum phosphates differ from those of iron phosphates. For example, negative charge and water retention increase with increases in Al-P/Fe-P ratio. In general, water retention of P-treated soils increases as a function of added P (Lutz, Pinto, Garcia-Lagos, and Hilton, 1966). For example, soils receiving P were moist, mellow and easy to plow; without P they were dry, hard, and difficult to plow.

### Ammonium Phosphate

*Literature.* Ammonium phosphate doubled the strength of soil after ten days contact (Kuhn, 1970). Diammonium phosphate,

$(\text{NH}_4)_2\text{HPO}_4$  produced the following reaction products in soil:  $\text{Ca}_4\text{H}(\text{PO}_4)_3 \cdot 2.5\text{H}_2\text{O}$ ,  $\text{Mg}_2\text{KH}(\text{PO}_4)_2 \cdot 15\text{H}_2\text{O}$ ,  $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$ , and  $\text{MgHPO}_4 \cdot 7\text{H}_2\text{O}$ —with the amounts of each product depending upon pH and type of soil (Subbarao and Ellis, 1975). The last two compounds formed in a neutral soil similar to Diablo clay. In addition to being a neutral compound, diammonium phosphate is also very soluble and thus easy to add in solution to the soil.

*Treatment.* Diammonium phosphate-treatment of Diablo clay produced nearly the largest decrease in the slope of shear curves and the largest increase in dry strength of all chemicals tested (Figure 34). The PL increased from 21 to 42 while the LL decreased only slightly. After leaching, the shear strength at high moisture contents increased as the LL increased from 84 to 112. This was similar to the dispersant effect produced by leaching the NaOH-treated soil (Figure 30).

According to Torrance (1974), intermediate amounts of dispersing agents like the hydroxides and phosphates are expected to lower the liquid limit of non-expansive quick clays. This of course was not true for Diablo clay, which is expansive. Five percent NaOH actually increased the LL from 86 to 89 (Figure 30). After leaching the excess NaOH from the sample, the LL

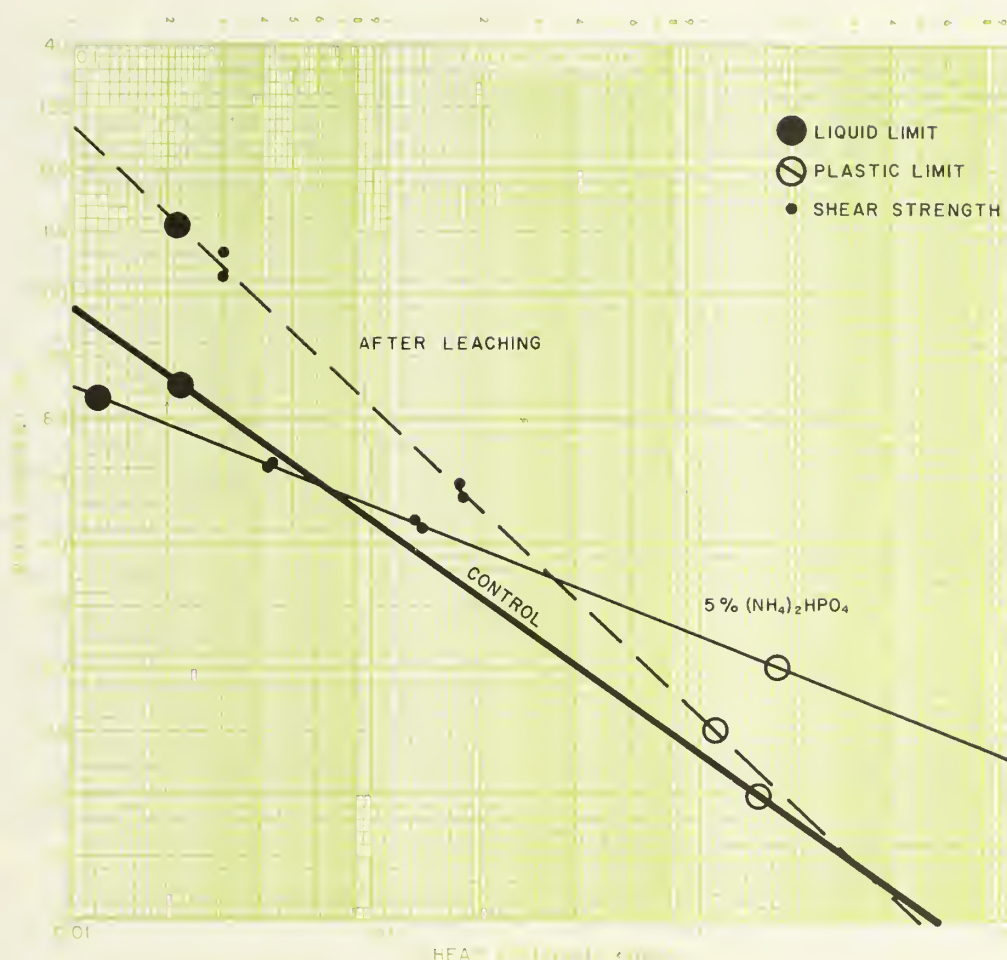


Figure 34. Shear curves for Diablo clay treated with 5% diammonium phosphate

increased to 161. These increases in LL for soil treated either with NaOH or diammonium phosphate correspond to improvements in strength at high moisture contents (compare Figures 30 and 34). Dispersants similar to these appear to increase the distance of interlayer separation by exchanging the natural divalent cations for monovalent cations. This was indeed the case for the ammonium cation. The LL of Diablo clay treated with 5% ammonium chloride increased from 60 to 96 after leaching (Figure 6). Also, the PL of Diablo clay increased to about 40 after treatment with 5% ammonium chloride—a result similar to that of treatment with diammonium phosphate. Likewise, the PL decreased to about 30 after leaching. The data for treatment with chlorides can reveal the effects of cation exchange when the excess salts are removed by leaching.

With diammonium phosphate, however, another possible explanation exists for the observed physical changes. This involves the precipitation of hydrated magnesium phosphates (Subbarao and Ellis, 1975), made especially likely because of the high proportion of exchangeable magnesium in Diablo clay (Table 1). The solubility of these compounds depends upon their hydration states. Solubility increases with each increase in the amount

of hydrated water. Also, the  $7\text{H}_2\text{O}$  hydrate forms from the  $3\text{H}_2\text{O}$  hydrate after 28 weeks (Subbarao and Ellis, 1975). Perhaps the temporary precipitation of magnesium phosphate simply accelerates the exchange of ammonium for magnesium. Magnesium phosphate may not be found in the soil because it may be soluble enough to be removed in the leachate. The result, however, would be a greater displacement of Mg by diammonium phosphate than by ammonium chloride.

### Calcium Phosphate

**Literature.** Calcium orthophosphate,  $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ , increased the strength of soil by nine times (Kuhn, 1970). The ordinarily low solubility of calcium orthophosphate can be increased dramatically by acidifying the solution with a small amount of phosphoric acid.

**Treatment.** Acidified calcium phosphate decreased the LL of Diablo clay from 86 to 72 and increased the PL from 21 to 29 (Figure 35). Unlike the results with most other chemical treat-



ments, these Atterberg limits did not change after the neutralization and leaching step. Shear strength increased at moisture contents less than 60%. Additional increases were obtained when the treated soil was neutralized and leached.

These increases suggest that the optimum pH was not obtained in the original treatment. Optimum  $H^+$  levels produced pH values between 2.3 and 3.5 for the phosphoric acid-treated soils studied by Hemwall and Scott (1962; pp. 40 and 47). The pH of Diablo clay treated with calcium phosphate and phosphoric acid was 4.5 (Table 5). The neutralization step was only partially successful, as seen by the reversion to a pH of 5.8 after the leaching step was completed. A gradual increase in pH takes place because equilibrium had not been reached during the temporary neutralization with about 20 meq of ammonium hydroxide (Table 5). With other types of chemical treatment, the slope of the shear curve usually increases after excess chemicals are neutralized and/or leached away (see for example, Figure 34). With acidic calcium phosphate, however, just the opposite seems to occur (Figure 35). This probably reflects continued precipitation of insoluble phosphate compounds that act as cementing agents. Such strength-enhancing effects can be considered relatively permanent.

### Phosphoric Acid

**Literature.** Extensive research has been done on phosphoric acid,  $H_3PO_4$ , for soil stabilization (Anonymous, 1962). Phosphoric acid exhibits variable effects on soil, but generally decreases the LL, PI, and potential volume change (Barenberg, 1963). Many methods of stabilization with phosphoric acid have been patented (Lyons, 1959b; Hemwall, 1963a and 1963b), but usage on landslides appears to be infrequent. Lutz and Pinto (1965) found that phosphoric acid softens field soils better than calcium phosphate. This may indicate that phosphoric acid reduces shear strength.

The shear strength of phosphoric acid-treated soil is highest when it is cured at an optimum water content (Barenberg, 1963). The strength-gains produced by the treatment tend to decrease rapidly with increasing water content. Stabilization effectiveness diminishes markedly when soils are cured at less than 100% relative humidity (Demirel, Benn, and Davidson, 1961; Barenberg, 1963).

**Table 5.** Titration and pH of Diablo clay treated with 5% amounts of phosphates.

CDMG No.	Treatment	$NH_4OH$ titrant, meq/100g	pH (paste method)
43/74	$(NH_4)_2HPO_4$	-	6.5
44/74	$(NH_4)_2HPO_4$ /leached	3	6.8
49/74	$H_3PO_4$	-	4.5
50/74	$H_3PO_4/NH_4OH$ /leached	21	5.6
55/74	$(Ca(H_2PO_4)_2 + H_3PO_4)$	-	4.5
56/74	$(Ca(H_2PO_4)_2 + H_3PO_4)/NH_4OH$ /leached	26	5.8
57/74	Control	-	7.4

**Phosphoric acid stabilization in relation to clay mineralogy.** Phosphoric acid stabilization is most effective with chloritic soils (Demirel, Benn, and Davidson, 1961). Also, phosphoric acid is more effective than lime for stabilizing chloritic soils (Demirel and Davidson, 1962) although it is several times more expensive (Ingles, 1968). Lime is more effective for reducing expansivity in smectitic soils.

The CEC of a clay soil increased from 14.5 to 53.4 meq/100 g after addition of 14% phosphoric acid (Demirel, Benn, and Davidson, 1961). This may have resulted either from formation of negatively charged aluminum phosphates or from de-chloritization of the clay. De-chloritization occurs when positively charged interlayer material is removed from chlorite to form a negatively charged, expansible clay such as montmorillonite. Conceivably, this process could counteract the cementing action of the insoluble phosphates of aluminum and iron. Fortunately, the test soil is primarily montmorillonitic with no significant amounts of chlorite. The results can be interpreted as due to the formation of cementitious compounds rather than interlayer removal.

At optimum pH levels, montmorillonite gains in unconfined compressive strength (Hemwall and Scott, 1962; Barenberg, 1963). Greater additions of acid decrease the strength of montmorillonite, but apparently not the strength of the more aluminous clays, mica-chlorite, kaolinite, and vermiculite. Phosphoric acid added to clayey soil in 2% amounts and cured for five days at 100% relative humidity produced fairly uniform stabilization (Lyons and McEwan, 1962). The potential volume change for beidellitic clay decreased from a measured value of 64% to a value of 0.02% after the treatment. Shear strength doubled after 30 days.

**Treatment.** Phosphoric acid decreased the plasticity index of Diablo clay (Figure 36), as did the lime and calcium phosphate treatments. The liquid limit declined from 86 to 73 while the plastic limit increased from 21 to 29. Similarly, the shear strength increased slightly at moisture contents below 60%. Neutralization and leaching produced further increases in shear strength, though the LL and PL remained the same. Torrance (1975) contends that phosphate ions decrease the LL because they act as a dispersant that increases interparticle repulsion. If this were the case for phosphoric acid, the LL would have increased after leaching. Phosphoric acid and calcium phosphate do not appear to be good dispersants for smectitic clay.

**Additives.** Additives for phosphoric acid stabilization of soils must be acidic or neutral. This fact also eliminates the practical usage of phosphoric acid for stabilizing soils that naturally contain large amounts of calcite,  $CaCO_3$ , or dolomite,  $CaMg(CO_3)_2$ . At least 1.25% phosphoric acid is needed to neutralize each 1% of calcite.

It appears that, in addition to lowering the pH, additives such as HF may enter into other reactions (Lyons, McEwan, and Siebenthal, 1962). As seen previously, the fluoride ion may form its own insoluble cementing agents. HF may be one of the best additives for phosphoric acid (and vice versa) because it forms insoluble precipitates with silicon. If so, HF would improve stabilization in soils high in Si, and the phosphoric acid would stabilize soils high in Al and Fe. Certainly, if this hypothesis should prove correct, it would widen the range of soil types that could be considered for stabilization by a single treatment.

**Effect of hydrofluoric acid as an additive.** Both phosphoric and hydrofluoric acid were added to Diablo clay in equal amounts (Figure 37). Shear strength increased at all moisture contents, but these results were no different than those with 3%



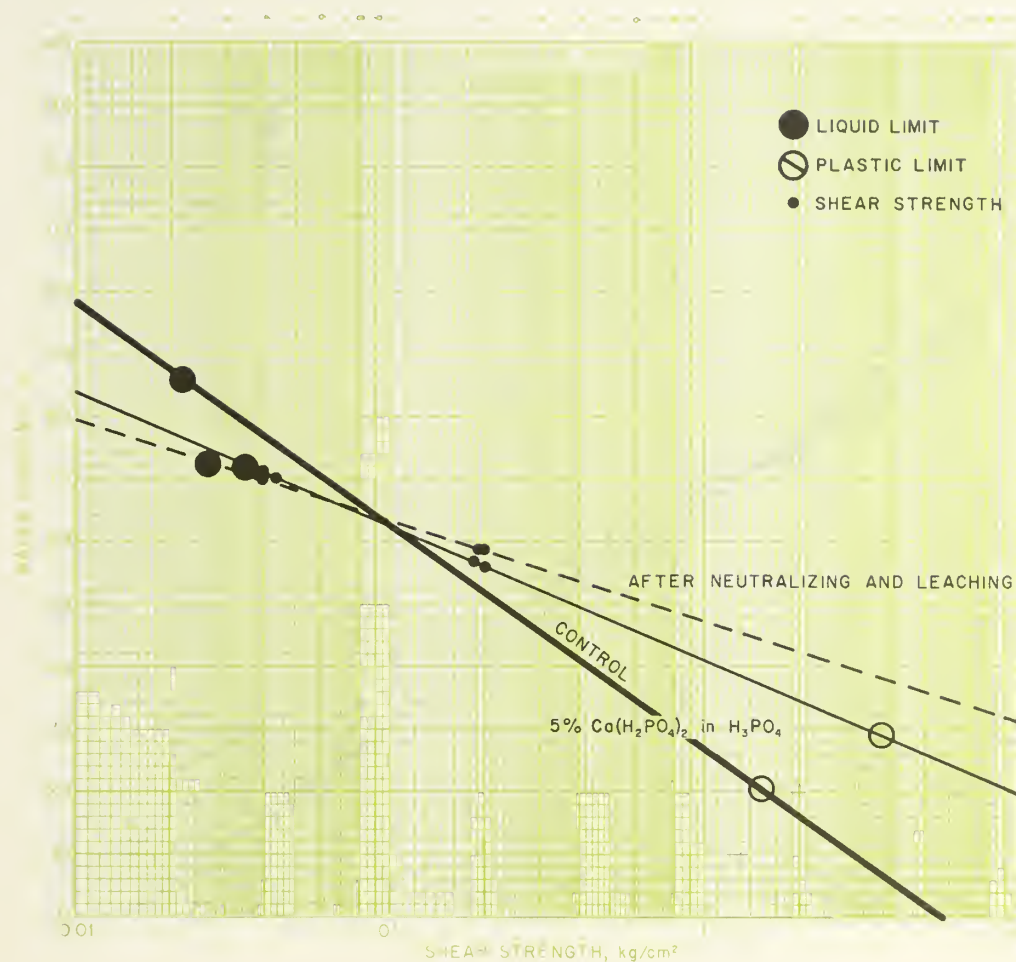


Figure 35. Shear curves for Diablo clay treated with 5% calcium phosphate and added phosphoric acid

HF alone (Figure 19). The curves even showed the gradual development of strength at high moisture contents that is characteristic of HF-treated soil (compare Figures 37 and 15). It can be concluded, therefore, that the strength-enhancing effects of phosphoric acid are either masked or overwhelmed by those of HF when equal amounts are used. Perhaps very small amounts of HF would be beneficial to stabilization with phosphoric acid.

### Sodium Phosphate

**Literature.** Most of the work involving sodium phosphate and shear strength is with quick clays. Talme (1968) reported that sodium hexametaphosphate ( $\text{Na}_6\text{P}_6\text{O}_{18}$ ), tetrplex ( $\text{C}_{10}\text{H}_{14}\text{N}_2\text{Na}_4\text{O}_8 \cdot 2\text{H}_2\text{O}$ ), and sodium pyrophosphate ( $\text{Na}_2\text{P}_2\text{O}_7$ ) caused at least a three-fold decrease in shear strength of quick clay. Sodium pyrophosphate, for example, caused shear strength to decline from 5.0 to 0.6  $\text{T/m}^2$ .

At high concentrations (0.5N) sodium hexametaphosphate promotes flocculation and increases the LL of quick clays (Torrance, 1975). This soluble phosphate causes soil dispersion because it blocks positively charged exchange-sites and complexes polyvalent cations that cause clay flocculation (Greenland, 1965).

**Treatment.** "Calgon" was previously the commercial name of alkaline sodium hexametaphosphate. However, Yaalon (1976) warns that "the currently marketed Calgon does not contain any soluble phosphates, and is hence no longer as effective for dispersing soils." Calgon purchased in early 1976 was used here, and it is therefore not clear whether or not it contained sodium hexametaphosphate. In any case, 5% Calgon increased the LL from 86 to 97 and the PL from 21 to 26 (Figure 38). These effects were accompanied by a slight increase in shear strength. The sample could not be leached with water because the clay remained dispersed at this concentration. About twice this much Calgon is routinely used to disperse soils for particle size analysis.

The increase in LL and shear strength of Calgon-treated soil is consistent with results for NaOH, another chemical used for dispersing clays (Figure 30). Once again, the expansive smectites in Diablo clay gave results opposite those of the non-expansive quick clays.

### Conclusions

The acidic phosphates form insoluble iron and aluminum precipitates that act as cementing agents in soils. The neutral

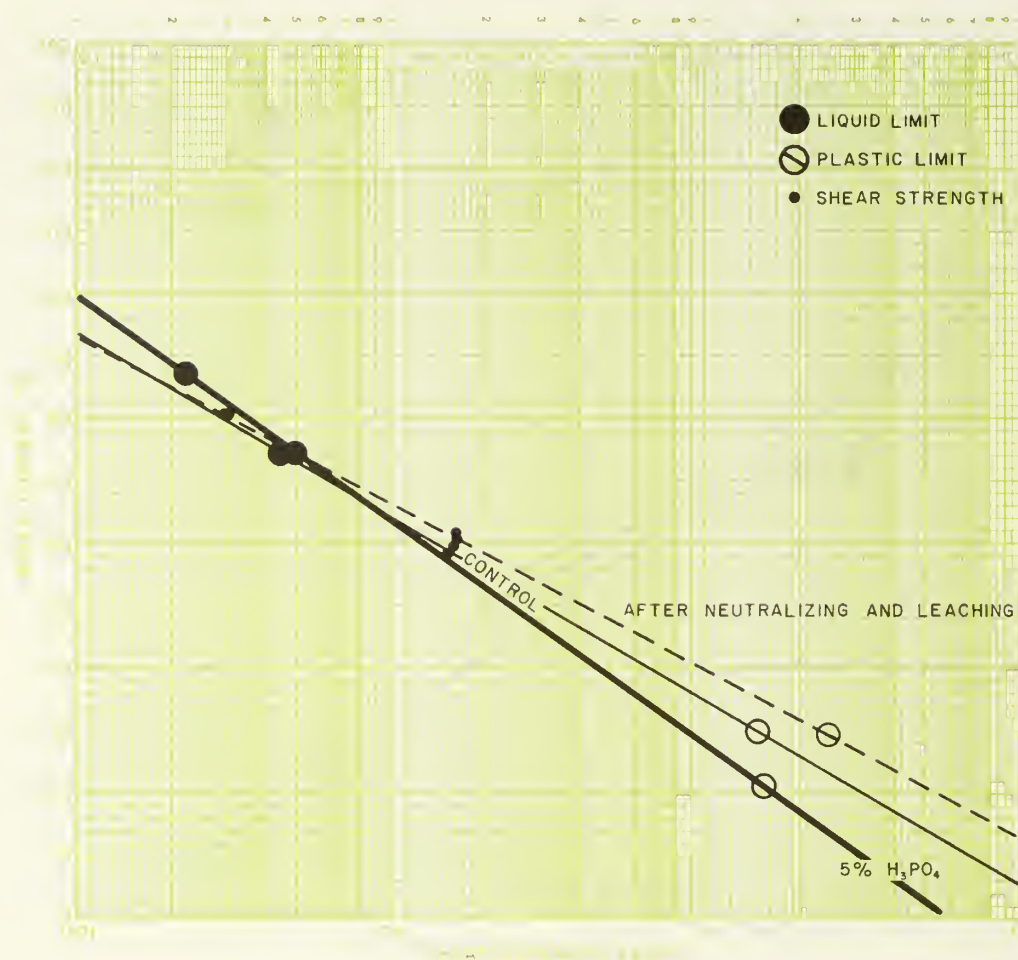


Figure 36. Shear curves for Diablo clay treated with 5% phosphoric acid

salt, diammonium phosphate, behaves much like other soluble salts. First, there is an increase in strength at low moisture levels and then, after leaching, there is an increase in strength at high moisture levels. The latter development occurs at the expense of strength at low moisture levels. However, when acidified calcium phosphate was added to Diablo clay, cementing agents formed. This treatment, as well as the treatment with phosphoric acid alone, increased shear strength at moisture contents below 60%. Subsequent neutralizing and leaching further enhanced this strength development. Thus, the acidic phosphates show promise for landslide stabilization in which permanence is a major factor.

## SULFATES

Sulfates range in solubility from the completely soluble sulfuric acid to the nearly insoluble calcium sulfate. The sulfates of Na, K, Mg, and Ca reduced the unconfined compressive strength of montmorillonite and kaolinite, but increased it for micaceous clay (Aufmuth, 1972).

### Aluminum Sulfate

**Literature.** A 5% solution of aluminum sulfate,  $Al_2(SO_4)_3 \cdot 17H_2O$ , did not change the LL, but increased the PL

of bentonite clay by 20-30% (Kerr and Drew, 1969). According to Kerr and Drew, however, the treatment decreased the direct shear strength at all moisture contents. This effect was attributed to sulfate and not to aluminum.

Another experiment (Kidder and Reed, 1972) showed that the swelling of a soil could be decreased from a value of 30.6% to a value of 0.6% when 1600 meq of aluminum sulfate was added to 100 g of soil and then titrated with NaOH to give 2.7 OH per Al. This reduced the cation exchange capacity of the soil to zero. Unfortunately, the shear strength was not tested. In any case, the large quantity of chemical (91 g/100 g of soil) required for such a treatment is clearly uneconomical for landslide stabilization. Aluminum sulfate also has been used with calcium ligno-sulfate to stabilize calcareous loess (Davidson and Demirel, 1960).

**Treatment.** Aluminum sulfate treatment (Figure 39) resulted in a slight decrease in LL and a 10-30% increase in PL. These results are similar to those of Kerr and Drew (1969). However, the significant decreases in direct shear strength that they reported were absent. In fact, there was a slight increase in low-moisture strength that appeared to remain unchanged after leaching. Thus, the sulfate anion does not appear to be detrimental to the strength of Diablo clay.



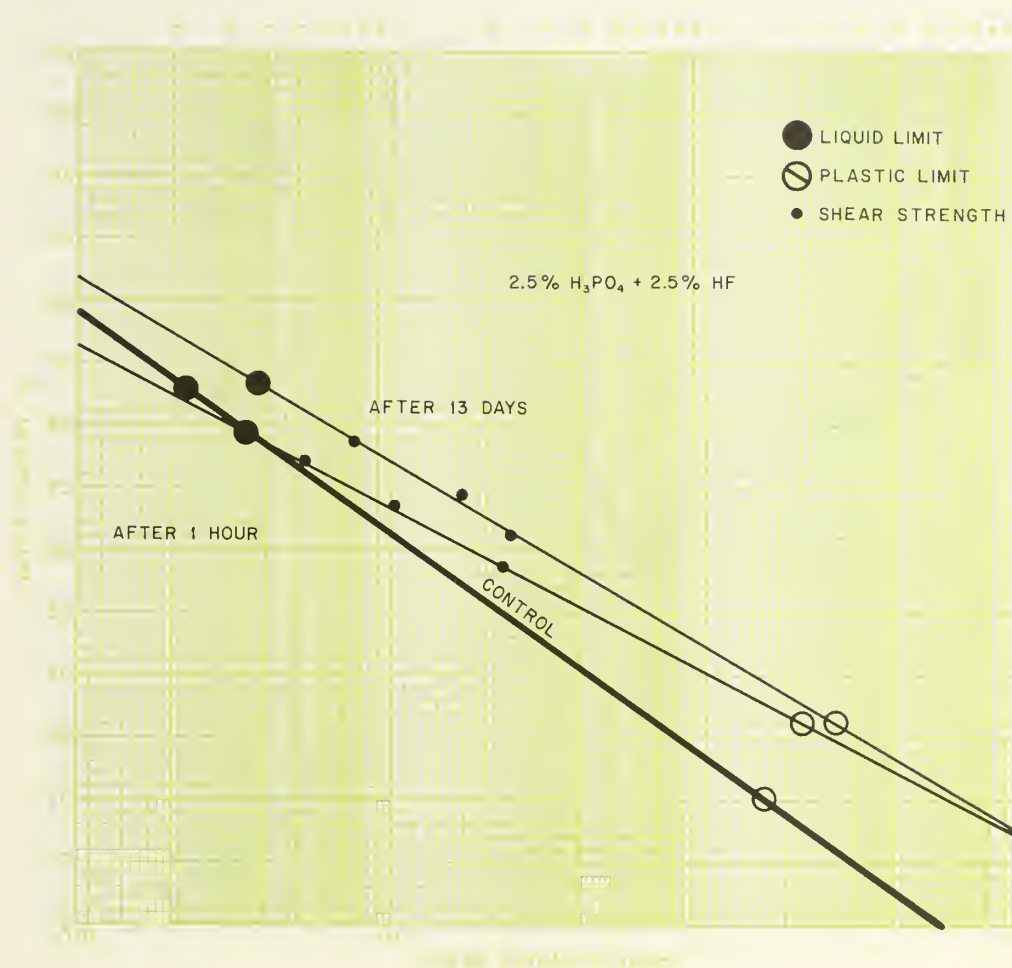


Figure 37. Shear curves for Diablo clay treated with 2.5% phosphoric acid and 2.5% hydrofluoric acid

### Ammonium Sulfate

**Literature.** We found no reports of the use of ammonium sulfate,  $(\text{NH}_4)_2\text{SO}_4$ , for chemical stabilization of landslides. Ammonium sulfate was included here to further evaluate the suggested detrimental effect of sulfates (Kerr and Drew, 1969). Also, testing ammonium sulfate would enable us to compare its effects with the effects of the other ammonium compounds already tested.

**Treatment.** As do other soluble salts, ammonium sulfate treatment of Diablo clay produced an increase in the PL (Figure 40). Unlike other salts, however, ammonium sulfate did not produce a decrease in the LL. Ammonium chloride (Figure 6), for example, depressed the LL and shear strength, but both ammonium sulfate (Figure 40) and ammonium phosphate (Figure 34) did not.

After leaching these samples of excess salts, the LL increased to values above that of the control sample. Also, the PL and shear strength of ammonium sulfate-treated soil decreased to normal after leaching (Figure 40). It appears that  $\text{NH}_4^+$ , like  $\text{K}^+$  (Figure 11), displaces a small amount of the  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  that occurs on Diablo clay in its natural state. This chemical exchange produces a slight elevation in the LL.

Only marginal and temporary increases in shear strength can be obtained with ammonium sulfate. Contrary to the suggestion of Kerr and Drew (1969), sulfate ions alone do not decrease the shear strength of smectitic clay.

### Calcium Sulfate

**Literature.** Calcium sulfate,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ , produces no change in shear strength according to Ingles (1968). This contrasts with the observations of Kerr and Drew (1969), who found that a 0.2% solution of calcium sulfate (gypsum) did not change the LL, but increased the PL by 20-30%. As with their experiments with aluminum sulfate, they also report that calcium sulfate decreases shear strength at all moisture contents.

Gypsum also has been used to decrease swelling in sodic soils through cation exchange of Ca for Na (Bridge and Tunney, 1973). Untreated Diablo clay, however, does not have enough exchangeable sodium to affect its physical properties in a significant way (Table 1).

**Treatment.** Calcium sulfate produced little significant change in smectitic clay (Figure 41). There was only a slight decrease in the LL and a slight increase in PL, and both returned to



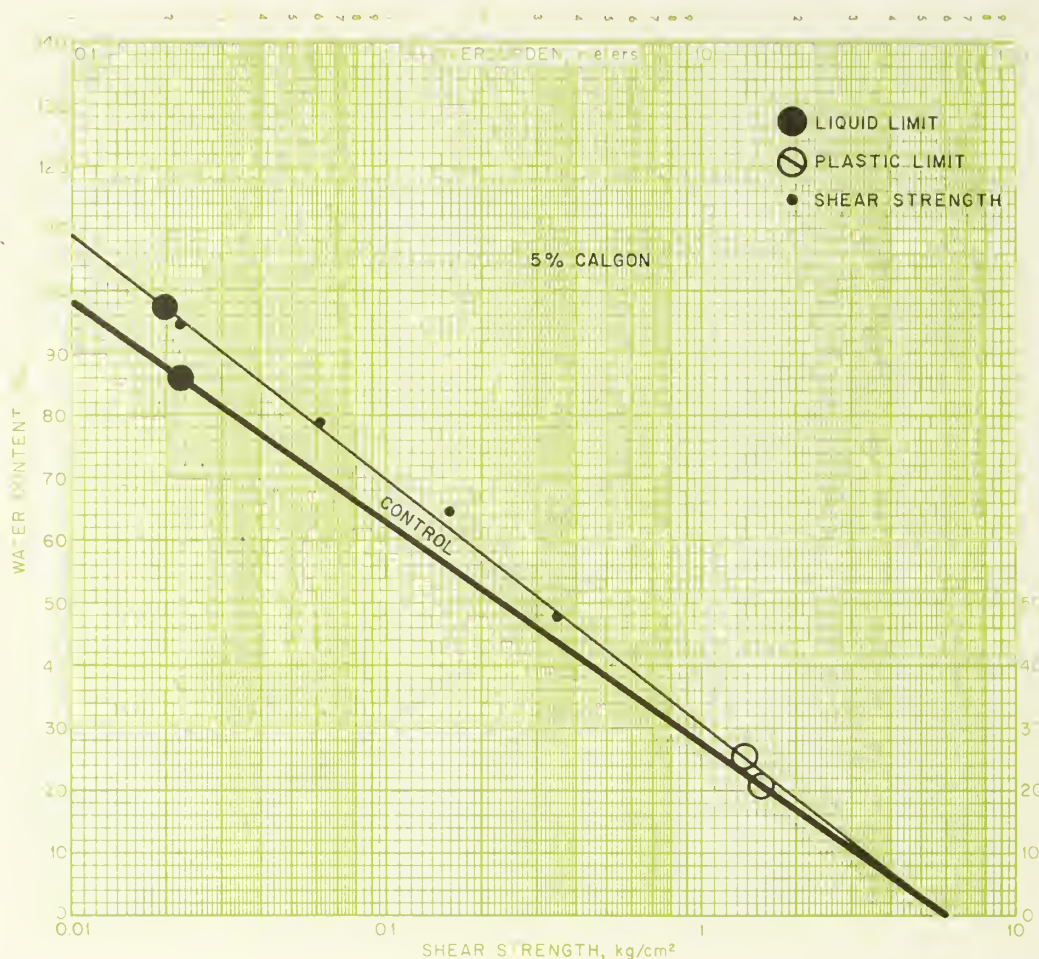


Figure 38. Shear curves for Diablo clay treated with 5% Calgon

normal after leaching. Changes in shear strength essentially were insignificant. Once again, sulfate did not appear to be detrimental to the shear strength of smectitic clay.

### Ferrous Sulfate

**Literature.** According to Arora and Scott (1974), the trivalent ions such as  $\text{Fe}^{3+}$  show more promise for landslide stabilization than the divalent ions such as  $\text{Fe}^{2+}$ . Unfortunately, ferric sulfate,  $\text{Fe}_2(\text{SO}_4)_3$ , would be difficult to use for chemical stabilization of landslides because it is relatively insoluble. However, the reduced form, ferrous sulfate ( $\text{FeSO}_4$ ), is very soluble and thus amenable to solution application to soils.

**Treatment.** The ferrous sulfate treatment slightly reduced the LL and the slope of shear curves for Diablo clay (Figure 42). Much of this change was recovered after leaching with distilled water. Some strength improvement occurred at low moisture contents. Cation exchange appeared to be minimal at this 5% level of application.

When ferrous sulfate-treated soil was neutralized with ammonium hydroxide first, and then leached, the LL nearly doubled to a value of 156 (Figure 43). Neutralization changed the shear curve from a type A curve (Figure 42 and 1a) to a type B curve (Figure 43) showing increases in shear strength at all moisture contents. The ferrous hydroxide produced by the addition of 61 meq of ammonium hydroxide had an average formula of  $\text{Fe}(\text{OH})_{1.6}^{0.4+}$  (Table 6). When ferrous sulfate-treated soil was allowed to dry slowly in air (6 months), neutralization with the hydroxide produced only small increases in shear strength, although the LL increased to 99 (Figure 43). Apparently, the exposure of ferrous iron to the oxygen in the air causes much of the iron to become oxidized to the ferric form, which has more modest strength-enhancing qualities than ferrous iron after neutralization and leaching (Figure 43). Also, ferric ion is likely to revert from the hydroxy form to the oxide form shortly after neutralization. Thus, the initial increases in shear strength produced by ferrous hydroxide are likely to decline through air drying or other oxidative processes. The long-term result of treatment with ferrous iron compounds is likely to be a type H curve (Figure 43) that appears characteristic of the short-term result of treatment with ferric compounds (Figure 8).

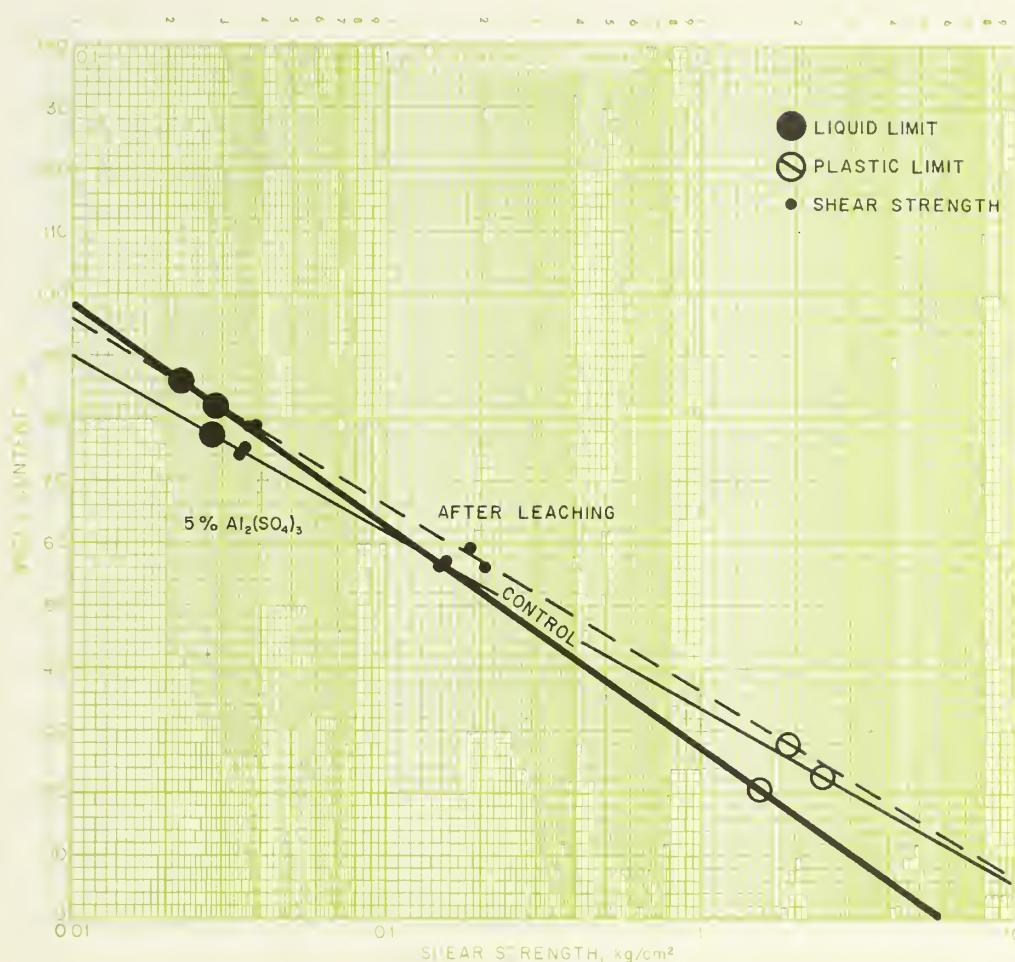


Figure 39. Shear curves for Diablo clay treated with 5% aluminum sulfate

Table 6. Titration and pH of Diablo clay treated with 5% ferrous sulfate (75 meq/100 g).

CDMG No.	Treatment	NH <sub>4</sub> OH titrant, meq/100 g	pH, poste method	OH/Fe
35/74	Moist	0	3.2	0
35B/74	Rapidly air dried and leached	0	3.9	0
36/74	Titrated with NH <sub>4</sub> OH to pH 7 and leached	61	6.1	1.63
52926172	Slowly air dried (6 months), titrated with NH <sub>4</sub> OH to pH 7, and leached	57	4.9	1.52
57/74	Control	0	7.4	-

*Ferrous hydroxide and smectite.* The initial and very pronounced effect of ferrous hydroxide on LL and shear strength is analogous to the behavior of the aluminum hydroxide system (Figure 4). Cohesion and water holding properties in both systems were increased considerably. It is unclear whether or not the hydroxy materials enter the interlayer space of the montmorillonite when neutralization occurs before leaching, but there are many obvious variables such as pH, rate of addition and type of hydroxide, presence or absence of leaching, permeability, etc., that need to be tested. Because type B curves are always accompanied by increases in LL, the progress of the neutralization could be monitored by simply measuring the liquid limit of treated soils.

Such a large increase in the liquid limit of ferrous iron-treated soil (LL=156) may indicate a reaction involving the entire surface area of the clay. Smectites have a surface area of 800 m<sup>2</sup>/g (Borchardt, 1977a). This includes both internal and external surface area, the external surface amounting to only about 5% of the total (Jackson, 1969, p. 332). A chemical reaction with an external surface area of only 40 m<sup>2</sup>/g probably would not produce much increase in the liquid limit. The internal surface,



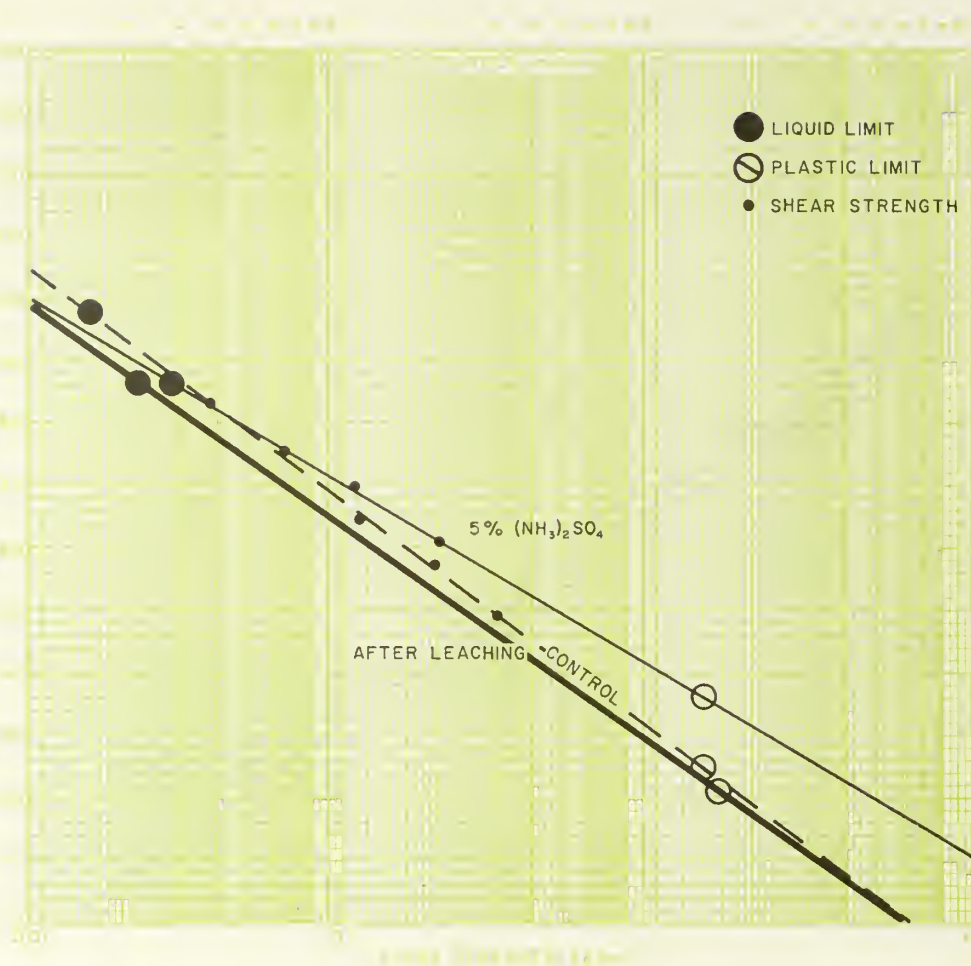


Figure 40. Shear curves for Diablo clay treated with 5% ammonium sulfate

on the other hand, is generally considered of major importance in water adsorption. With chemical reactions affecting the internal surfaces, increases in internal water adsorption would probably appear as increases in the LL. The amount of water associated with each true monolayer of water on all surfaces of montmorillonite can be calculated as follows:

$$\begin{aligned}
 \text{Number of water molecules per gram of montmorillonite} &= \frac{800 \text{ m}^2/\text{g} \times 10^{20} \text{ A}^2/\text{m}^2}{10.8 \text{ A}^2} \\
 &= 7.4 \times 10^{21} \\
 \text{Number of moles of water per gram of montmorillonite} &= \frac{7.4 \times 10^{21} \text{ molecules}}{6 \times 10^{23} \text{ molecules/mole}} \\
 &= 0.0123 \text{ mole} \\
 \text{Weight of water per gram of montmorillonite} &= 18 \text{ g/mole} \times 0.0123 \text{ mole} \\
 &= 0.22 \text{ g} \\
 \text{\% water for monolayer on montmorillonite} &= \frac{0.22 \text{ g} \times 100}{1.0 \text{ g}} = 22
 \end{aligned}$$

Because the test soil, Diablo clay, is less than 50% montmorillonite, less than 11% water is needed to produce a true monolayer of water on the sample. Thus, the calculated value compares favorably with the actual percentage of moisture in the air-dried soil, 10% (Table 1). The increase in LL from 85 to 156 would increase the number of water layers on the clay from 7.7 to 14.2. If external surface alone was responsible for water adsorption and increases in LL, the number of water layers on each particle would be at least ten times this: 77 to 142—an unlikely prospect.

Another method of assessing the very large change in LL produced by ferrous hydroxide treatment concerns the number of water molecules associated with each ferrous ion. The addition of 0.0375 mole of ferrous sulfate caused the liquid limit to increase by 70 g/100 g of oven-dry soil (3.888 mole of water). Dividing the number of moles of water by the amount of iron gives approximately 100 water molecules per Fe molecule. This amount of water might simply be characteristic of  $\text{Fe}(\text{OH})_2$ , a "greenish gelatinous hydrous precipitate" (Laubengayer, 1957, p. 503). The precipitation of ferrous hydroxide is likely to develop some shear strength in any solution in which it is included.



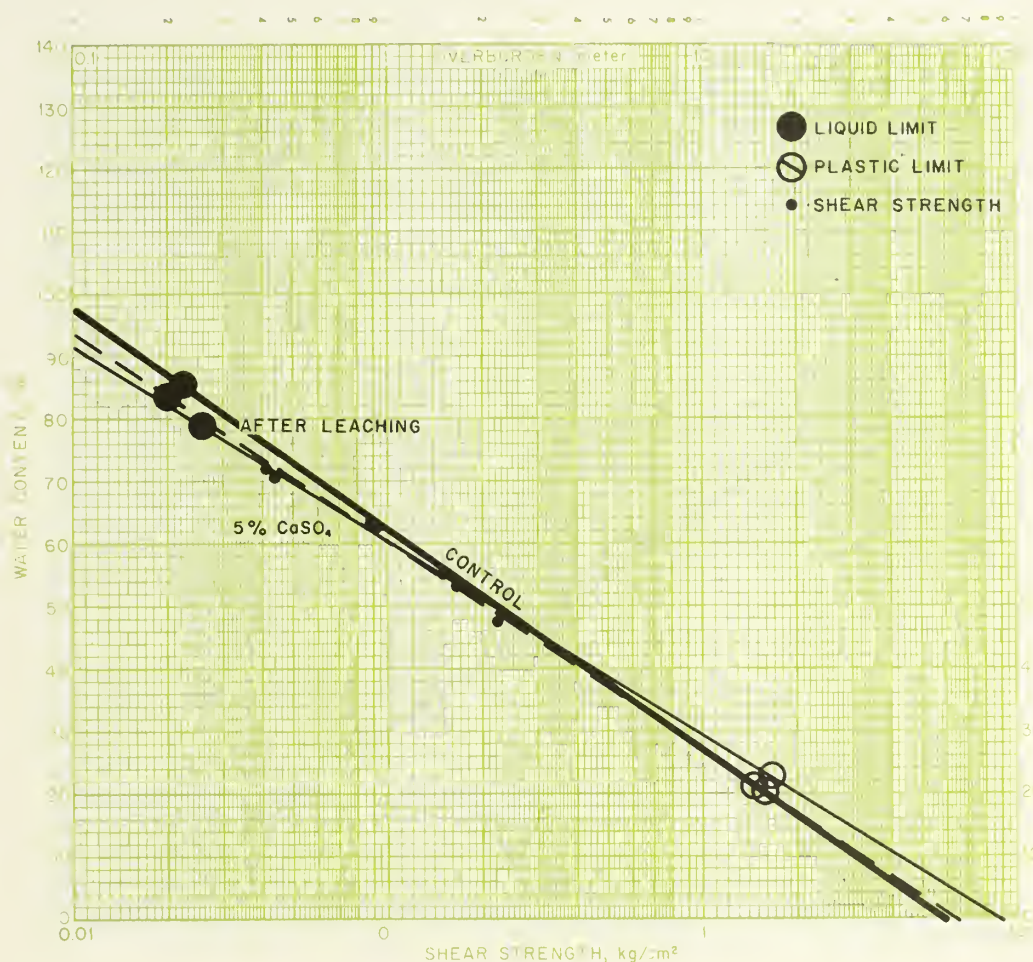


Figure 41. Shear curves for Diablo clay treated with 5% calcium sulfate

**Ferrous hydroxide and kaolinite.** Kaolinite has no internal surface area. Thus, any reactions involving ferrous hydroxide and kaolinite would involve only external surfaces. We tested this by adding ferrous sulfate to Ward's No. 5 kaolinite (Figure 44). Neutralization and subsequent leaching of the excess soluble salts brought about an increase in the LL from 26 to 35. This was accompanied by a slight increase in the PL from 16 to 19. Shear strength increased at moisture contents above the PL. Overall, the effect of the treatment on the physical properties of kaolinite was minimal.

If the formation of ferrous hydroxide gel is responsible for the small increases in the Atterberg limits that did occur, then it would affect only the external surfaces of the kaolinite. Under similar conditions, the LL of Diablo clay increased from 85 to 156 while the PL increased from 21 to 26. Thus, some of the ferrous hydroxide must have formed within the internal surfaces of the expanding montmorillonite and beidelite in Diablo clay. This is consistent with the results for aluminum hydroxide (Figure 4). The hydroxide forms interlayers in montmorillonite, as we demonstrated by removing the excess aluminum chloride

prior to the neutralization step. The result was an H-type curve with increased shear strength at all moisture contents. On the other hand, kaolinite has only external surface area and, therefore, its increase in LL was much less than for the smectites.

Apparently, the PL is not affected by interactions with inter-layer surfaces. Thus, the type of movement that occurs at the plastic limit apparently occurs mostly on an inter-particle level. Movement at the LL apparently occurs on an intra-particle level, that is, when the individual layers of an expanding clay move over each other during liquid flow. A coating of ferrous hydroxide on these internal surfaces probably increases the requirement for water to lubricate the movement.

Ferrous hydroxide increased the PI of Diablo clay by 65 (Figure 43). If Diablo clay were 100% montmorillonite, the PI would have increased by a value of approximately 130. This is more than 20 times the increase in PI (6) noted for pure kaolinite. Likewise, the total surface area and cation exchange capacity (CEC) of smectite generally is considered to be at least 20 times both the surface area and CEC of kaolinite. The ferrous hydroxide-clay interaction thus involves internal as well as external surfaces.

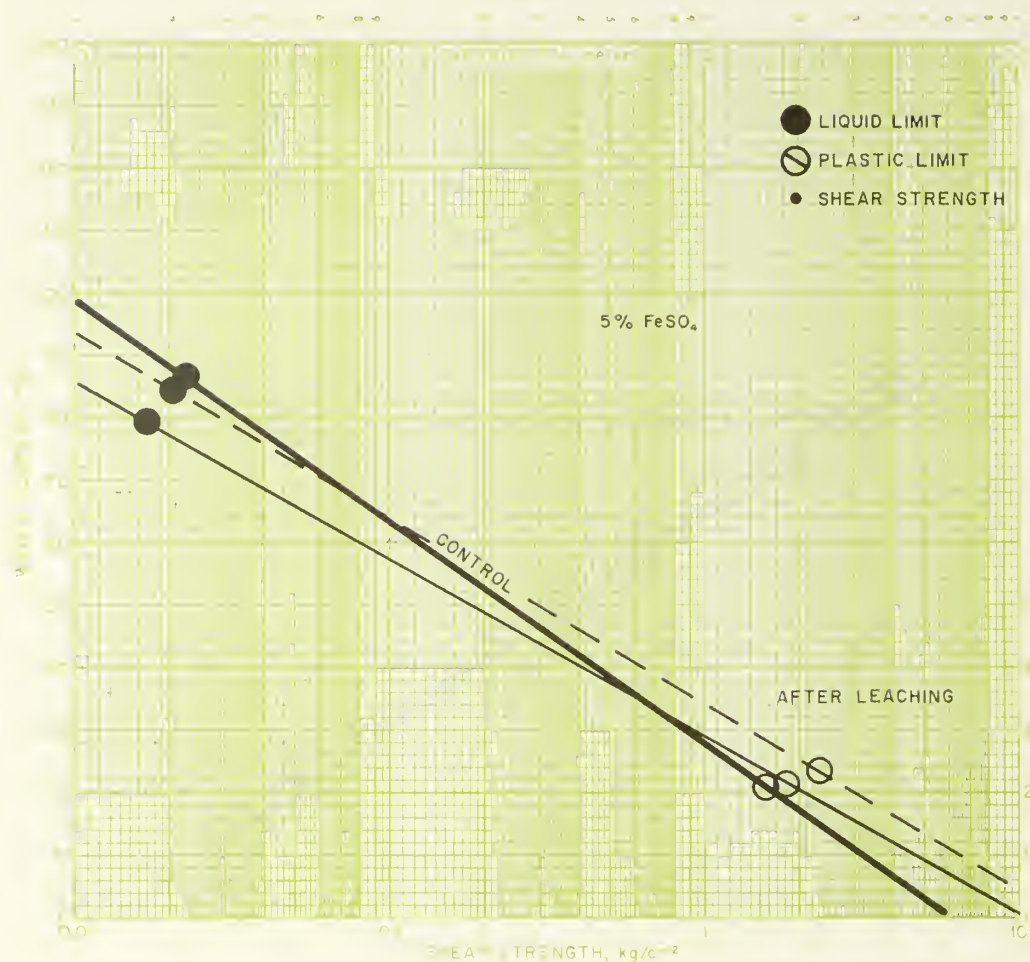


Figure 42. Shear curves for Diablo clay treated with 5% ferrous sulfate

As a matter of interest, this reaction might be of some use in developing methods for the quantitative determination of expanding clay minerals. For example, both nontronite (an iron containing smectite) and noncrystalline material have CEC's of 100 meq/100 g (Alexiades and Jackson, 1966), but only nontronite has interlayer surface area. Perhaps ferrous hydroxide treatment of nontronite would produce large increases in LL, but noncrystalline material would not be affected because it lacks the same type of internal surface area.

*Implications for testing soils containing ferrous iron.* Two important factors have important implications for the measurement of the physical properties of soils containing ferrous iron. These factors are (1) the ease with which ferrous iron is oxidized in the air and (2) the tendency for ferrous hydroxide to increase the liquid limit. Free iron generally amounts to 1% or more of the soil. Soils with high water tables and negative redox potentials would be likely to have high amounts of ferrous iron, which could occur either as exchangeable ferrous ion or as nonexchangeable ferrous hydroxide, depending on the pH. When such soils are sampled and then processed in the laboratory, the ferrous iron would be oxidized through the air drying step that is

part of the usual procedure for liquid limit determination. "In some clays, such as those containing halloysite or members of the montmorillonite group, drying has profound and often unpredictable effects on the consistency limits" (Sowers, 1965, p. 394).

Soils containing ferrous iron should be allowed only limited contact with the air if dependable results for LL and shear strength are sought. Wet sieving would be necessary to get the less than 420  $\mu$ m material needed for the tests. The redox potential of the soil should remain as close to field conditions as possible.

Even though air drying is avoided, a pessimistic view of the possibility of keeping ferrous iron from oxidizing must be taken. For example, the routine determination of ferrous iron in soils involves a freshly taken sample in field moist condition, with the entire extraction of ferrous iron taking 5 minutes or less. Oxidation of the ferrous iron can amount to 20 % in 15 minutes and up to 80% in 60 minutes (Jackson, 1958, p. 391). Ferrous iron was almost completely oxidized in highly reduced soils during 1 or 2 days of air drying (Jackson, 1958). Obviously, more work needs to be done in developing procedures to determine the true physical properties of soils containing reduced iron.



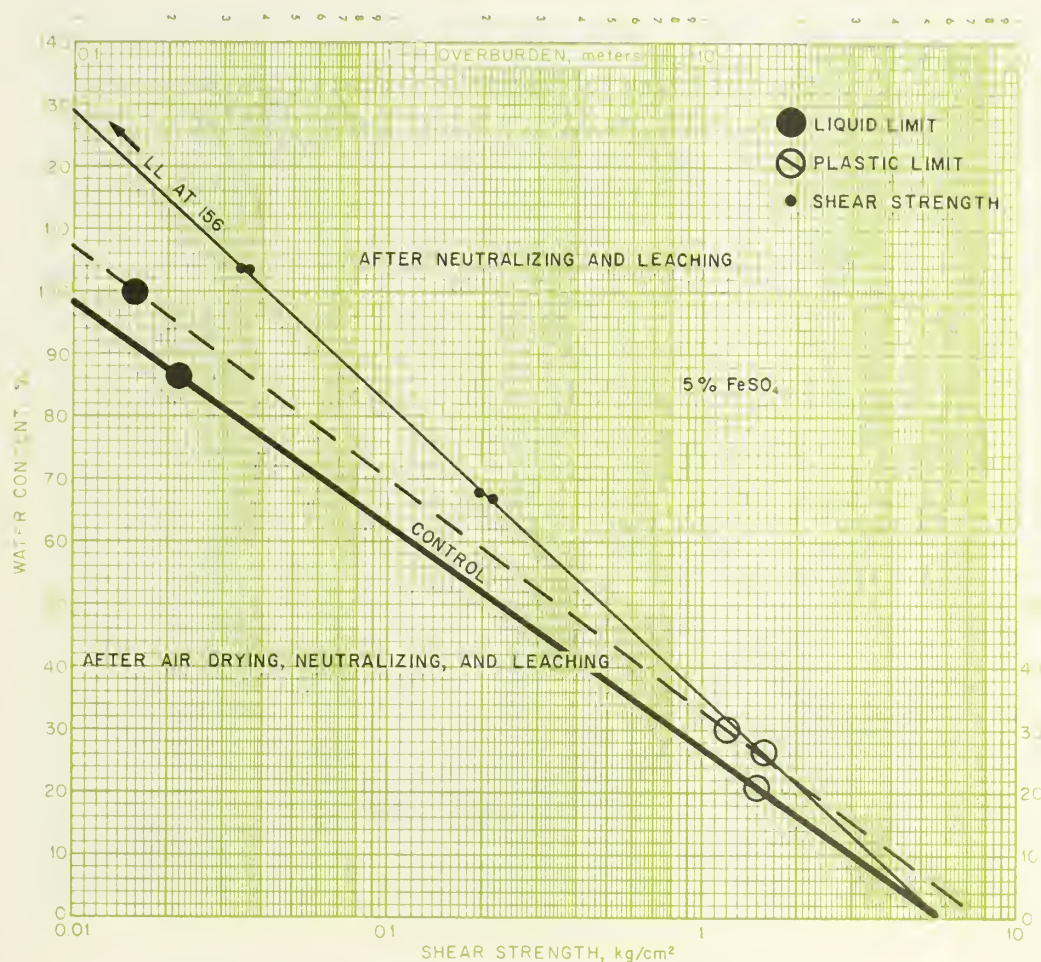


Figure 43. Shear curves for Diablo clay treated with 5% ferrous sulfate after neutralizing and leaching

The plasticity index, for example, which is an important measure of the swelling potential of a soil (Seed, Woodward, and Lundgren, 1962), could be grossly distorted through oxidation of ferrous iron in the test sample. This problem is likely to be significant only in samples from poorly drained soils. Also, soils that are under the influence of a changing water table, or even of changing water contents, would be expected to have changing liquid limits and shear strengths. As an illustration, extractable  $\text{Fe}^{2+}$  varies from 140 to 5 ppm in an Oregon soil in which the water table fluctuates from 0 to 130 cm in depth below the soil surface (Somera, 1967, p. 43). Fortunately, shear strengths would have a tendency to increase during the rainy season when increasing moisture contents normally produce a decrease in shear strength. Perhaps redox measurements would be helpful information for soil engineers.

### Sulfuric Acid

**Literature.** Sulfuric acid,  $\text{H}_2\text{SO}_4$ , improved the strength of phosphoric acid-treated soil (Hemwall, 1963a). According to

Moum, Sopp, and Loken (1968), sulfuric acid takes part in many complicated chemical reactions in soils. Sulfuric acid is expected to give results similar to those with iron and aluminum. This is because acid treatment of clay tends to release  $\text{Fe}^{3+}$   $\text{Al}^{3+}$  from the clay structure (Harward and Coleman, 1954). The released iron and aluminum then behave as if they were added as soluble salts.

**Treatment.** Sulfuric acid treatment of Diablo clay merely produced a slight decrease in the LL and shear strength at high-moisture levels (Figure 45). Neutralizing and leaching, however, returned the LL to normal and increased the low-moisture strength. A similar shear curve was found for the phosphoric acid treatment (Figure 36). A significant difference between neutralized and leached sulfuric and phosphoric acid treatments is that the LL remains depressed with phosphoric acid, but returns to normal with sulfuric acid.

Hemwall and Scott (1962) noted an improvement in shear strength when sulfuric acid was added with phosphoric acid. Additions of soluble aluminum sulfate resulted in anomalous decreases in strength whenever both sulfuric and phosphoric



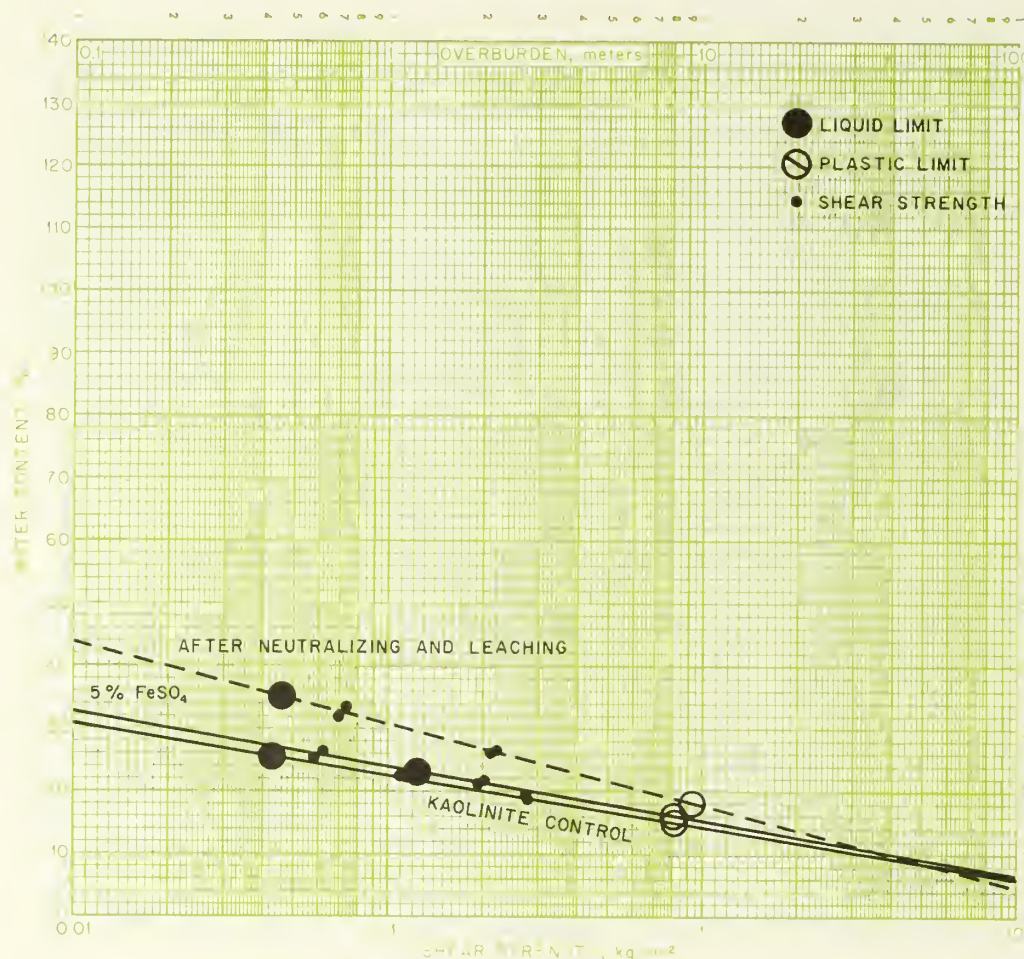


Figure 44. Shear curves for Ward's No. 5 kaolinite treated with 5% ferrous sulfate

acid were also present in the soil. Aluminum sulfate decreases the shear strength of montmorillonite at all moisture levels according to Kerr and Drew (1969).

As mentioned previously, acids such as hydrochloric and sulfuric cause  $\text{Fe}^{3+}$  to be released from soil minerals. The released iron has a tendency to combine with the anion of the acid that was added. Soluble ferric chloride,  $\text{FeCl}_3$ , tends to form in the HCl-treated soil. Insoluble ferric sulfate,  $\text{Fe}_2(\text{SO}_4)_3$ , tends to form in a soil treated with sulfuric acid. Ferric chloride is soluble in HCl whereas ferric sulfate is insoluble in sulfuric acid. Precipitation of ferric sulfate would thus lower the solution concentration of  $\text{Fe}^{3+}$ , causing even more  $\text{Fe}^{3+}$  to be removed from the soil. For this reason, sulfuric acid would remove much greater amounts of iron from the soil minerals than hydrochloric acid during the one-month aging period. Subsequent neutralization and leaching of excess sulfuric acid and sulfate salts then reveals an increase in shear strength (Figure 45).

### Conclusions

Aluminum sulfate increased the shear strength of Diablo clay at low moisture levels. Ammonium sulfate produced only mar-

ginal and temporary increases in shear strength. Calcium sulfate produced no significant change in physical properties. Ferrous sulfate doubled the liquid limit and increased the shear strength at high moisture levels after the neutralizing and leaching step. This last effect was not nearly as great when the soil was air dried prior to neutralizing and leaching. This demonstrated that the oxidation of iron from the ferrous to the ferric state could affect the measurement of the physical properties of certain iron-rich soils that are normally found in a reduced state beneath the water table. In order to get values applicable to the natural state, such soils should not be air dried prior to testing.

The ferrous sulfate treatment also was performed on a non-expansive clay mineral, kaolinite. The failure of this treatment of kaolinite to produce dramatic increases in LL and shear strength showed that ferrous sulfate treatment produces such dramatic increases only in soils in which ferrous hydroxide can precipitate between the layers of an expansive clay. The smectite in the test soil, Diablo clay, is such an expansive clay.

Sulfuric acid increased shear strength at low moisture levels. However, this effect was noticed only after the neutralizing and leaching step. The insolubility of ferric sulfate in sulfuric acid may be responsible for some of the effectiveness of sulfuric acid.

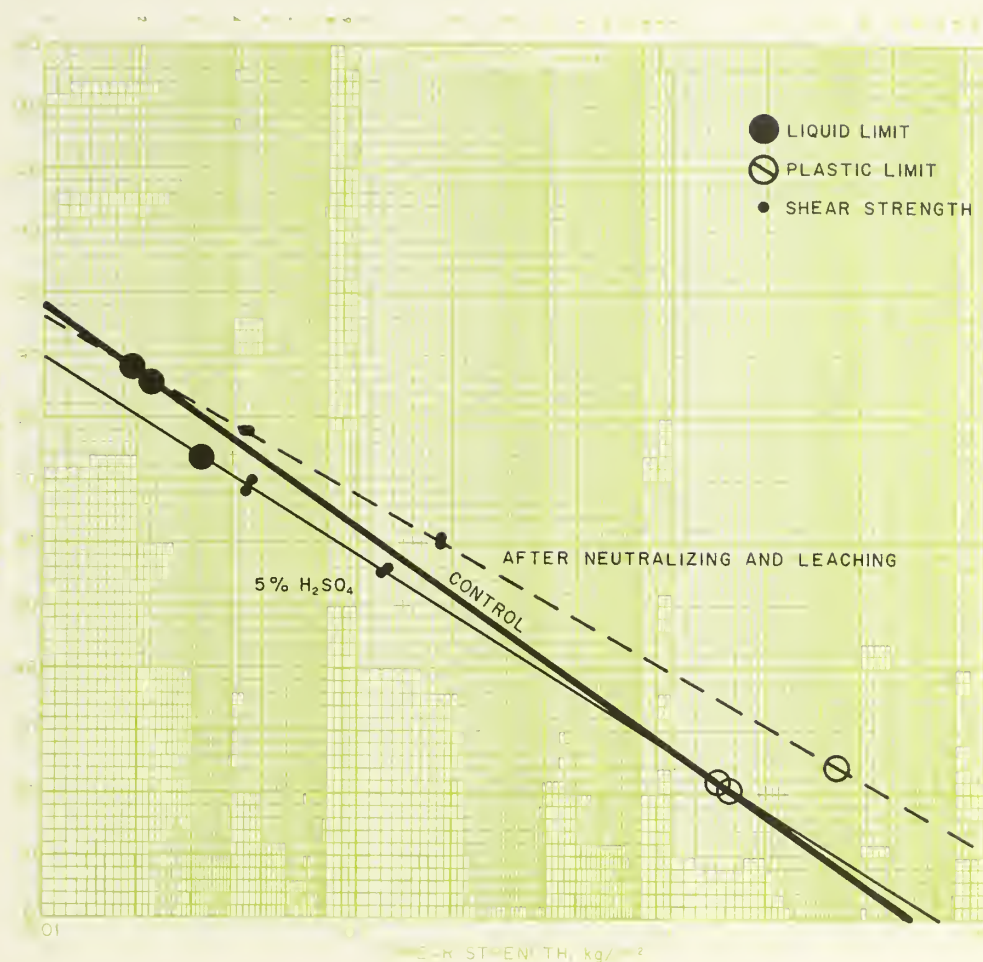


Figure 45. Shear curves for Diablo clay treated with 5% sulfuric acid

## OTHER CHEMICALS

Certain chemicals were tested that do not fit any of the above groups. These were included for reasons unique to each case.

### Sodium Metasilicate

**Literature.** Sodium metasilicate ( $\text{Na}_2 \cdot x\text{SiO}_2$ ), also called "water glass," increased the shear strength of quick clay when calcium chloride was included (Talme, 1968). Otherwise, shear strength decreased. Within two hours of mixing, sodium metasilicate reacted with sodium fluosilicate,  $\text{Na}_2\text{SiF}_6$ , to form silica,  $\text{SiO}_2$ , and  $\text{NaF}$  or  $\text{HF}$  (Burrows, 1966). Such inorganic consolidants can hydrolyze, resulting in soluble salts that work against the usefulness of the consolidants as strengthening agents (Knopman, 1975). The literature on sodium silicate stabilization of soils was reviewed by Hurley and Thornburn (1971).

**Treatment.** Sodium metasilicate is commonly used to disperse soil aggregates for particle size analysis. Dispersion occurs when

individual clay particles within a soil become electrocharged in such a way that they repel each other. The particles then become physically separated when they are in a water suspension. The presence of one gram of sodium metasilicate per 100 grams of soil generally is sufficient to bring about dispersion.

The addition of 5 grams of sodium metasilicate ( $\text{Na}_2\text{SiO}_3$  equivalent) to 100 grams of Diablo clay brought about large increases in LL and shear strength (Figure 46). The LL increased from 86 to 117 while the PL increased from 21 to 27. Leaching of the excess salts caused a further increase in the LL to 132, with a small increase in shear strength. The treatment would be remarkably stable, at least with respect to the leaching aspects of soil weathering. Further work concerning the effects of neutralization would be necessary.

This dispersed system, like that of the sodium hydroxide-treated soil, probably would have a lowered permeability that would result in a gradual increase in total adsorbed moisture. This would be counteracted by improvement in strength at all moisture contents. Other types of soluble silicates such as potassium metasilicate should also be tested.



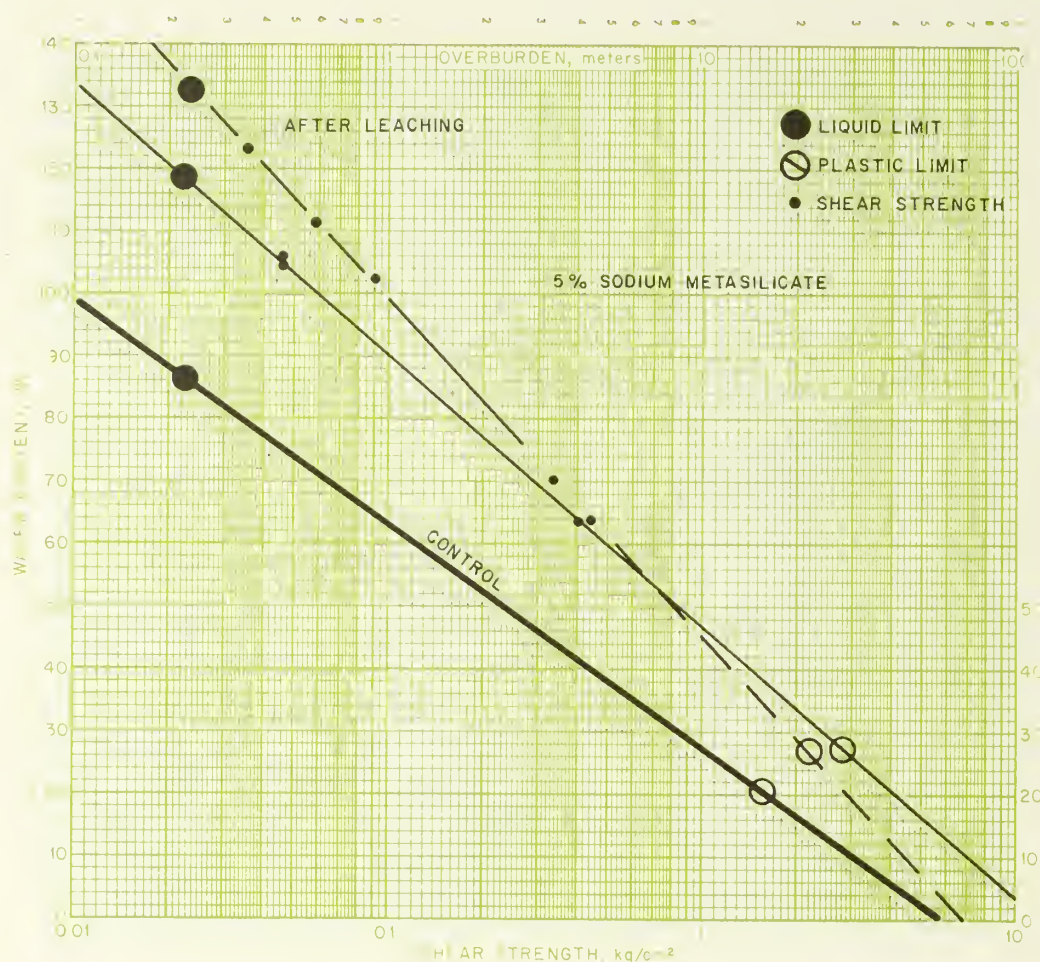


Figure 46. Shear curves for Diablo clay treated with 5% sodium metasilicate

### Potassium Iodide

**Literature.** Potassium iodide, KI, has not been used for chemical stabilization of landslides. We wanted to check potassium iodide because of its relationship to the other halides. KCl produced the usual decrease in LL and increase in PL common for soluble salts (Figure 12). KF increased both LL and PL (Figure 20). When KCl-treated soil was leached, the LL increased to a value above normal, while the PL returned to normal. When KF-treated soil was leached, LL, PL, and shear strength remained above normal.

**Treatment.** As a treatment of Diablo clay, KI behaved like other soluble salts by decreasing LL and increasing PL (Figure 47). After leaching, these values returned to normal and no change in shear strength resulted from the treatment. There was a significant difference between KCl and KI in response to leaching. The increased LL of KCl-treated soil indicated that some K had been exchanged for natural Mg or Ca. With KI this did not occur. Likewise, there was no evidence of the formation of insoluble precipitates as in the reaction of KF with soil. KI, therefore, does not appear useful for stabilizing smectitic landslides.

### Ferrous Sulfate and Calcium Hydroxide Mixture

**Literature.** In earlier discussions, it was noted that calcium hydroxide increased the low-moisture strength of Diablo clay (Figure 26). Similarly, ferrous sulfate-treated soil increased high-moisture strength when the pH was increased to produce ferrous hydroxide in the interlayer space (Figure 43). Equal proportions of both chemicals were used in the following experiment to see if such a mixture would increase strength at both low and high moisture contents (type H shear curve). Calcium hydroxide and ferrous sulfate also appeared ideal for this purpose, because the high pH of the lime would tend to provide the environment for ferrous hydroxide formation.

**Treatment.** Equal portions of ferrous sulfate (2.5 g unhydrated equivalent) and calcium hydroxide (2.5 g) were added to 100 grams of Diablo clay. After one hour of contact, the LL decreased slightly from 86 to 81 while the PL increased from 21 to 32 (Figure 48). Shear strength measurements showed that a type H curve was not achieved. In general, the results were dominated by calcium hydroxide (compare Figure 26) rather than by ferrous hydroxide produced from ferrous sulfate (com-

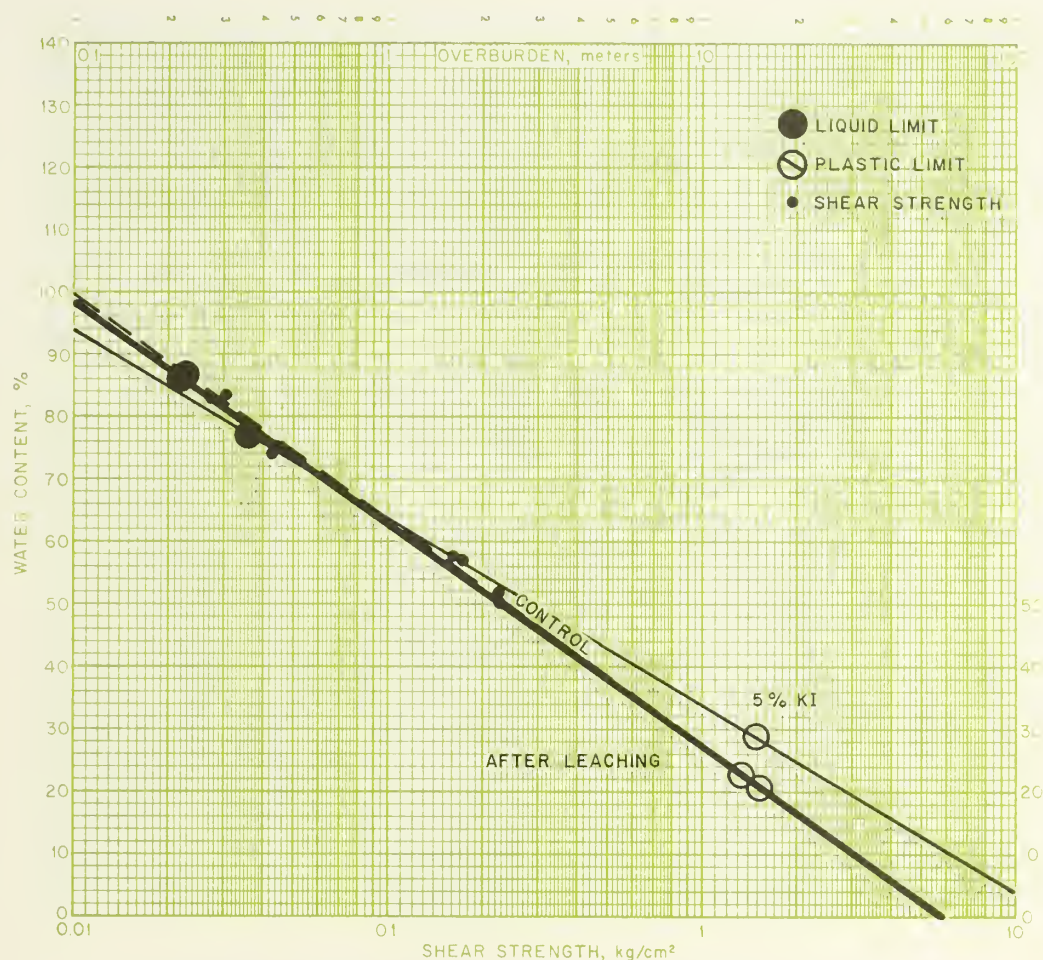


Figure 47. Shear curves for Diablo clay treated with 5% KI

pare Figure 43). No change was observed in the mixture after 75 days, except for a decrease in the PL from 32 to 26 (Figure 48).

Ferrous sulfate prevented the usual dramatic increase in PL shown by lime-treated soils. Further studies on the reactions involved may lead to a better understanding of calcium hydroxide adsorption by smectite. Work on mixtures of chemicals may eventually lead to one that will increase shear strength at all moisture contents while fulfilling the practical requirements of application to a wide variety of landslides.

### Ferric Oxide and Iron Powder

**Literature.** Ferric oxide,  $\text{Fe}_2\text{O}_3$ , increased soil strength by three times at six days, but by only 30% after ten days contact (Kuhn, 1970). Iron powder has not been tested for landslide stabilization. Both of these materials must be physically mixed with soil, but both should give some idea of the effects of diluting the soil with "inert materials."

**Ferric oxide treatment.** Ferric oxide essentially did not change the physical properties of Diablo clay (Figure 49). What might

be considered a slight improvement in strength at low moisture contents occurred, but this was never more than a doubling of strength. Unlike the results reported by Kuhn (1970), a tripling of strength at six days followed by a reduction in strength was not observed.

**Iron powder treatment.** Iron powder was mixed with Diablo clay and kept in contact with the soil for 41 days. This resulted in small increases in the LL and PL, and moderate increases in shear strength at all moisture levels (Figure 50). This curve is remarkably similar to the one produced by neutralizing and leaching-treated soil with ferric chloride (Figure 8). Both iron powder and ferric chloride are likely to produce hydrated forms of iron such as  $\text{FeOOH}$  rather than  $\text{Fe}_2\text{O}_3$ . These hydrated forms of iron would not be exactly comparable to ferric oxide,  $\text{Fe}_2\text{O}_3$ .

Iron oxide powder would be expected to increase remoulded shear strength by increasing internal friction rather than cohesion. These materials are highly insoluble and, thus, it is unlikely that they would be useful for landslide stabilization. Even so, studying them, as well as the soluble compounds, may provide information about stabilization reactions.



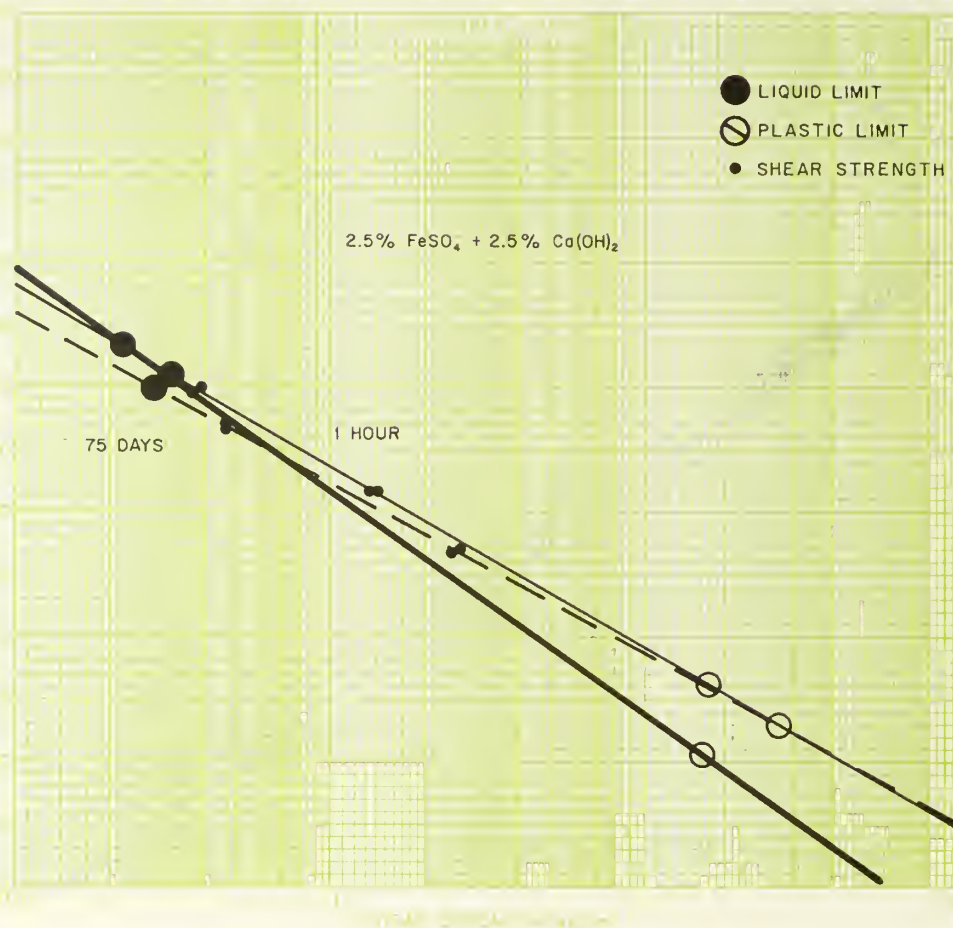


Figure 48. Shear curves for Diablo clay treated with 2.5% ferrous sulfate and 2.5% calcium hydroxide mixture

### Aluminum Nitrate

*Literature.* Aluminum nitrate,  $\text{Al}(\text{NO}_3)_3$ , increased the shear strength of a soil by a factor of three (Kuhn, 1970). Aluminum nitrate was included to further test the ion exchange theory and to compare its effects with those of aluminum chloride and aluminum sulfate.

*Treatment.* Aluminum nitrate-treatment of Diablo clay decreased the LL from 86 to 71 without changing the PL or the shear strength (Figure 51). This contrasts with other soluble salts such as aluminum chloride (Figure 3) that produced greater decreases in high moisture strength and increases in low moisture strength.

Neutralizing with ammonium hydroxide and leaching with water caused the LL to increase to 138 and the PL to increase to 33 (Figure 51). Shear strength increased dramatically at moisture contents above 20%. This was similar to results for aluminum chloride (Figure 4) and ferrous sulfate (Figure 43).

Most likely, these results are produced through interlayer formation, as previously explained.

### Conclusions

Sodium metasilicate produced large increases in the liquid limit and in shear strength at all moisture contents. This improved strength persisted after leaching. Metasilicates should be investigated for changes in soil permeability that might increase the moisture contents of landslides.

Potassium iodide does not appear useful for stabilizing smectitic landslides. Soil treated with a mixture of calcium hydroxide and ferrous sulfate was dominated by calcium hydroxide—shear strength was improved only at low moisture levels. The ferrous sulfate prevented the decreases in expansion normally achieved with calcium hydroxide treatment.

Ferric oxide essentially did not change the physical properties of Diablo clay. Iron powder slightly increased the shear strength at all moisture levels. Thus, the hydration of iron compounds other than ferric oxide appears to produce minor increases in shear strength.

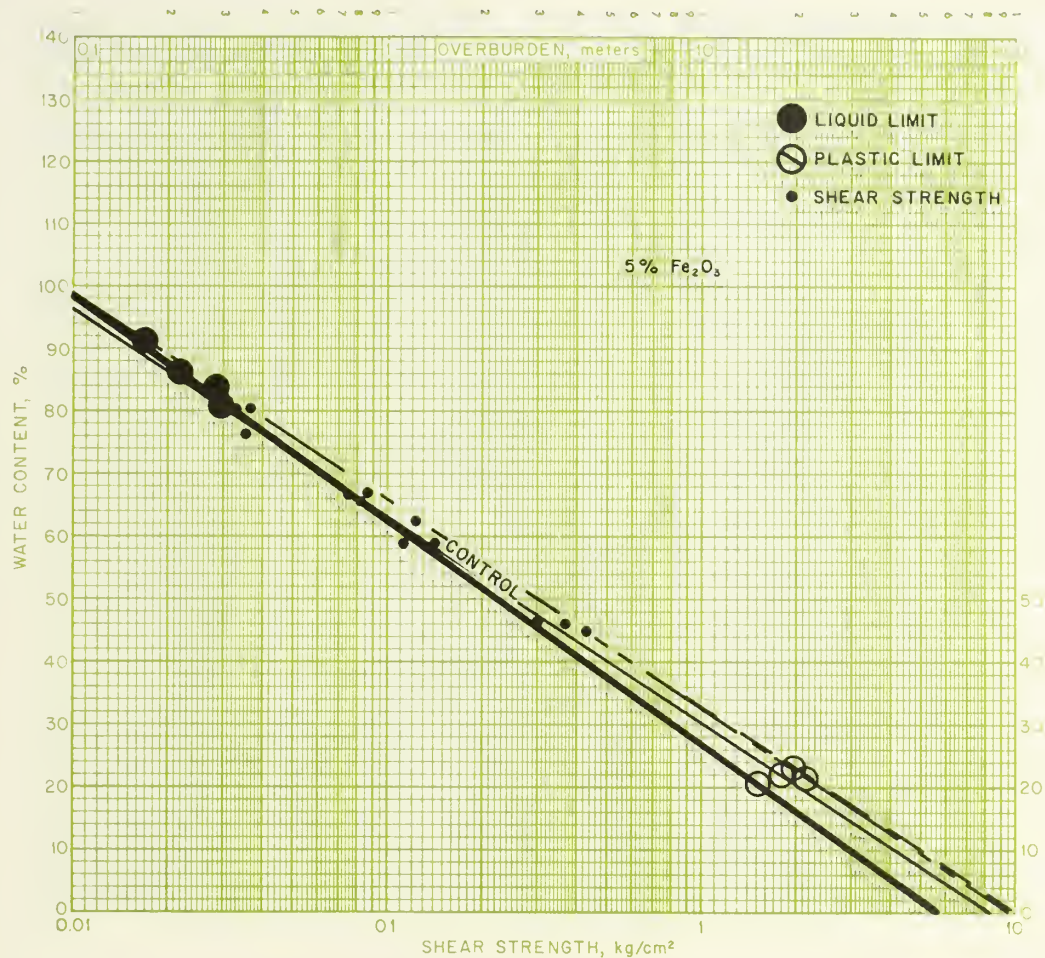


Figure 49. Shear curves for Diablo clay treated with 5% ferric oxide

Aluminum nitrate reduced the LL without reducing the shear strength significantly. After neutralizing and leaching, the aluminum nitrate-treated soil displayed a tremendous increase in LL. There were corresponding increases in shear strength at high moisture levels. Most likely, these results are produced through aluminum hydroxy interlayer formation in smectites, as was noted for ferrous iron and other aluminum systems.

## SUGGESTIONS FOR FURTHER TESTING

Certain chemical treatments increase shear strength of smectitic soil, both before and after neutralizing and leaching. Specifically, these chemicals are:

Hydrofluoric acid  
Potassium flouride  
Sodium hydroxide

Calcium phosphate (acidified)  
Phosphoric acid  
Sodium metasilicate

These chemicals should be investigated in detail for the following:

- (1) optimum rates of application
- (2) variation of behavior in relation to mineralogy
- (3) reaction products formed
- (4) nature of stabilizing mechanism
- (5) methods of application
- (6) permeability changes
- (7) most economical chemicals to use
- (8) results with other methods of evaluating shear strength
- (9) adverse environmental consequences
- (10) situations where untoward results would be expected
- (11) rates of diffusion of the chemical through soil
- (12) other criteria found applicable to stabilization of landslides



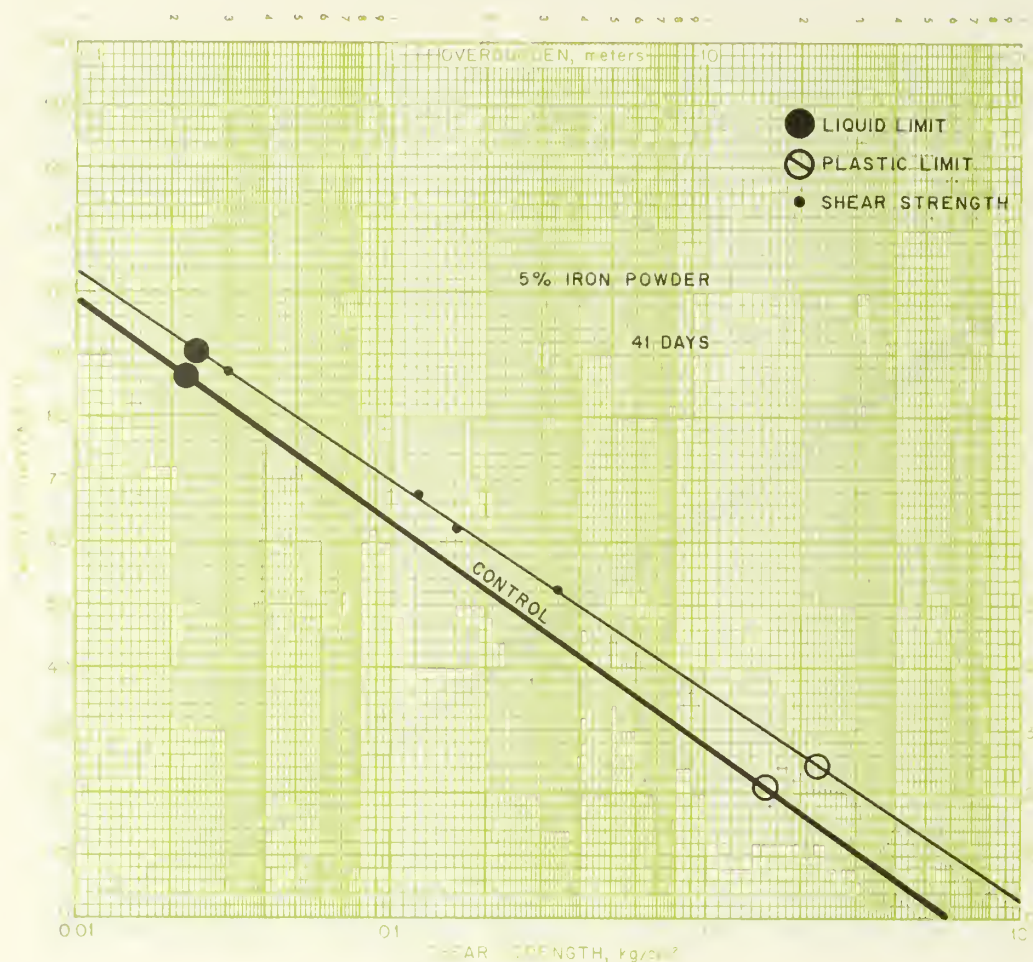


Figure 50. Shear curves for Diablo clay treated with 5% iron powder

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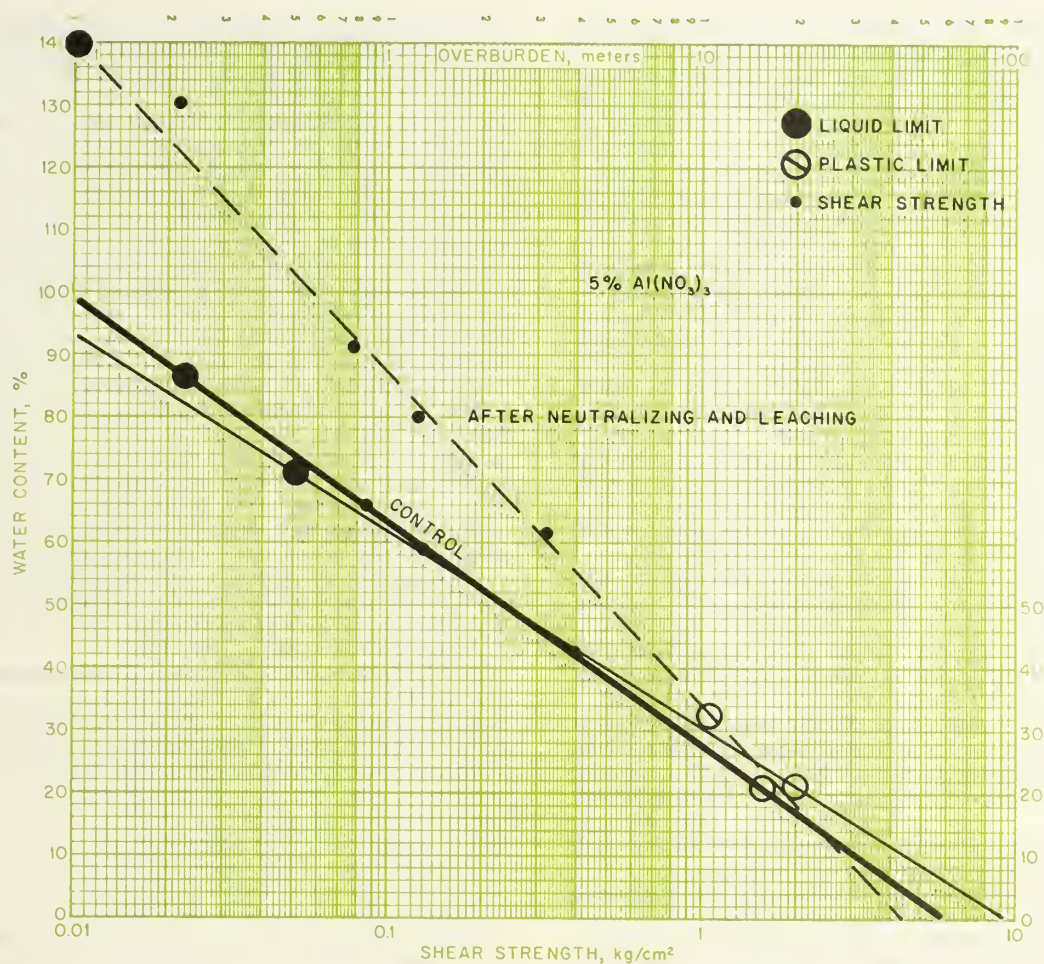


Figure 51. Shear curves for Diablo clay treated with 5% aluminum nitrate

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